"New Approaches in Inkjet Printing on Flexible Substrates: Patterning for OLED Applications": *Ghassan Jabbour,* Professor and Director of Optoelectronic Materials and Devices, **Arizona State University.** Dr. Jabbour outlined activities related to the use of hydrogen peroxide as an environmentally and printer friendly oxidizer for patterning (by inkjet printing) of PEDOT-PSS coated PET films. He showed that sheet resistivity via inkjet and variable resistance applications can be controlled with little degradation associated with hydrogen peroxide. Surface roughness appeared better after oxidation, while optical transparency was unchanged.

Examples of inkjet patterning on flexible substrates using sheet resistance adjustment at Arizona Statue University

"Unlocking the Potential of AMOLED": *Damoder Reddy,* President/CEO, **Nuelight Corporation.** This presentation was the first time that Nuelight had publicly announced what they are doing. Dr. Reddy started his presentation with a rather eye-opening summary of the many problems still facing the OLED industry. He listed problems associated with image sticking, differential color aging, lifetime, TFT uniformity and stability, inadequate manufacturing infrastructure, low yields, and high costs. According to Reddy, "any BOM cost advantages enjoyed by OLEDs are thrown away due to inadequate OLED utilization and low production yields.

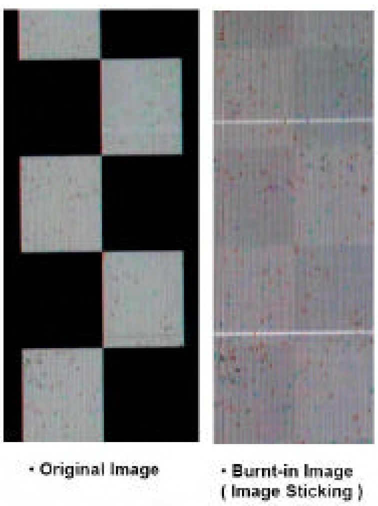


Image sticking problem on this checkerboard pattern is visible at only 98% OLED color dearadation

According to Reddy, perhaps the most glaring problem facing OLED manufacturers today is related to image sticking. He asserted, "OLED displays look beautiful as long as you don't ever use it'. The problem of image sticking is primarily related to differential color aging. OLED manufacturers tend to measure color degradation in relation to the time it takes to reach 50% of the original color. The problem with this approach is that image sticking is visible at 98% – not 50%. The problem is very serious – even for mobile phone displays where display lifetimes may not be so important due to short device lifetimes. Development of stable OLED materials to eliminate image sticking is at least 10 years away, according to Reddy. Rather than focusing on improving the OLED materials, some manufacturers are experimenting with compensating circuits to improve TFT uniformity. While important, this approach doesn't solve the optical problems associated with the OLED.

Reddy introduced Nuelight's solution to this image sticking problem – the development of an ASIC to serve as an emissive feedback system. An optical sensor is built into every TFT. Then by correction algorithms, the ASIC can adjust the brightness of each pixel. Reddy described this as an electronic solution that does not solve the fundamental problem of image sticking, but masks the problem, extending the life of the OLEDs to essentially eliminate an obvious degradation associated with image sticking. Although the solution adds some costs at the driver IC level, there are no additional costs at the backplane level. Amorphous silicon AMOLEDs with Nuelight's pixel circuit have been built with standard a-Si TFT processes.

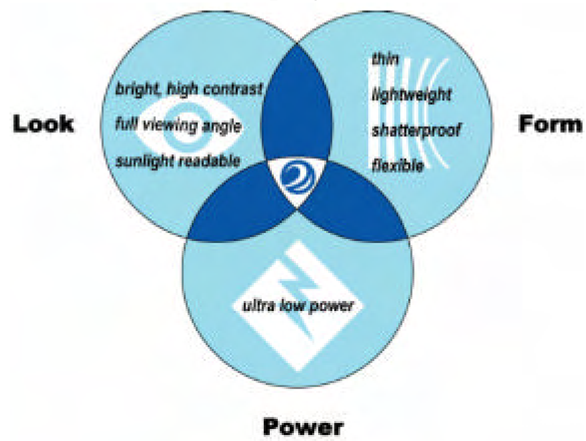
iSuppli Flat Information Display Conference

8-9 November 2005, San Francisco, California

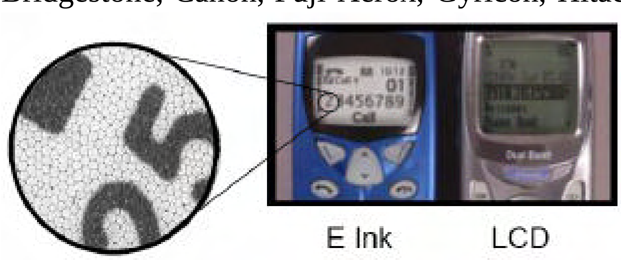
Several of the presentations at this year's running of iSuppli's Flat Information Display Conference were related to flexible substrates. In this issue, *Mark Fihn* summarizes four of the presentations, from E Ink, DuPont, Plastic Logic, and Universal Display. The remaining presentations will be discussed in the next issue of the *Flexible Substrate.*

"E Ink: Technology Platform for Electronic Paper Displays": *Russ Wilcox*, CEO, **E Ink.** Wilcox gave an optimistic summary of the future of electronic paper, hinting toward broad adoption in numerous existing market segments and the creation of yet-to-be-identified future segments. The thrust of his presentation was to identify the huge opportunities available for electronic paper. For example, he cited that today the display industry is approaching $100 billion in revenues – but the printed paper industry represents some $400 billion in annual revenues – a figure that exceeds the annual revenues of the music, movie, and video gaming industries.

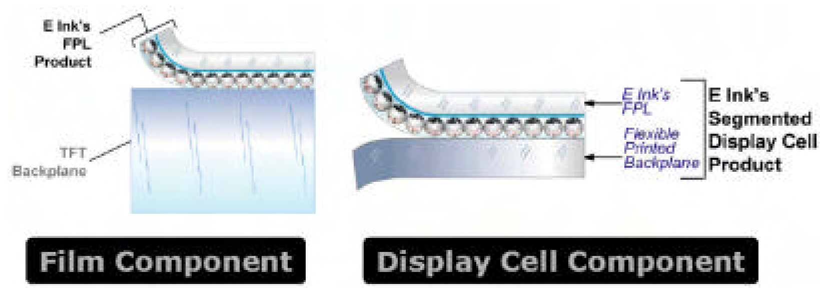
To be successful as a device to bridge the gap between printed documents and computer displays, Wilcox suggested that electronic paper must display an image with resolution and other attributes that stop eye strain and enable improved reading speeds and comprehension; provides handheld access to printed documents and publications; and dramatically increases screen size and battery life for all devices. He argued that only electronic paper displays (EPDs) could satisfy these multiple requirements for devices that have the opportunity to displace a substantial portion of the printed paper industry. The "perfect EPD", according to Wilcox, combines reflectivity, bistability, and flexibility. Such displays will vie for predominance in multiple applications, including e-books, electronic dictionaries, office Tablets, large-area signage, wearable devices, automotive and transportation devices, smartcard readout, segmented displays, portable monitors, and electronic newspapers.



Wilcox went on to identify that at least twenty companies have been developing EPDs, using a variety of technologies, (bistable LCD, chemical, MEMS, and colored pigments. E Ink is in the latter category, along with Bridgestone, Canon, Fuji-Xerox, Gyricon, Hitachi, LiquaVista, Ricoh, Minolta, Seiko-Epson, and SiPix. Although the different companies using colored pigment technologies have somewhat different implementations, in each the pigments are encapsulated and physically move based on the application of an electronic impulse. To date, more than $120 million has been spent on the development of pigmented solutions over the past eight years. The technology is protected by 76 patents, with more than 200 patents pending.



E Ink's technology is divided between two primary display product types. For high-resolution active matrix displays, E Ink sells an open-faced film laminate (FPL) to TFT LCD manufacturers that is applied to the TFT backplane. For low-resolution segmented displays, E Ink has developed a finished display cell which includes the FPL and the backplane. These cells are sold directly to integrators and OEMs in the electronics industry. Wilcox showcased a variety of technology partners that have implemented one of the E Ink solutions in the past two years.



Included in the E Ink technology showcase were Sony Japan's high-resolution Librie e-book reader, passenger information displays from Vossloh and Toppan, Citizen's cellphone sub-display and changeable barcode solutions, Philips' smartcard, Seiko-Epson watch, point-of-purchase displays by Neolux, Citizen's clock (which reportedly can run for 10 years on a 2 AA batteries), and a new e-book reader from the Chinese company Jinke (*shown below*). E Ink has also developed a prototype kit that helps prospective clients quickly build breadboard designs.

Wilcox also revealed some roadmap plans for E Ink's product developments. In early 2006, the company will unveil a faster solution (improving from about 1-3 frames per second to 3-6 frames per second. In the second half of 2006, E Ink will release full-color displays using an RGBW approach (prototypes have already been demonstrated); and by mid-2007, E Ink will show off all-plastic, flexible displays.

e-book reader from Jinke uses E Ink technology

Full color from E Ink, available at the end of 2006

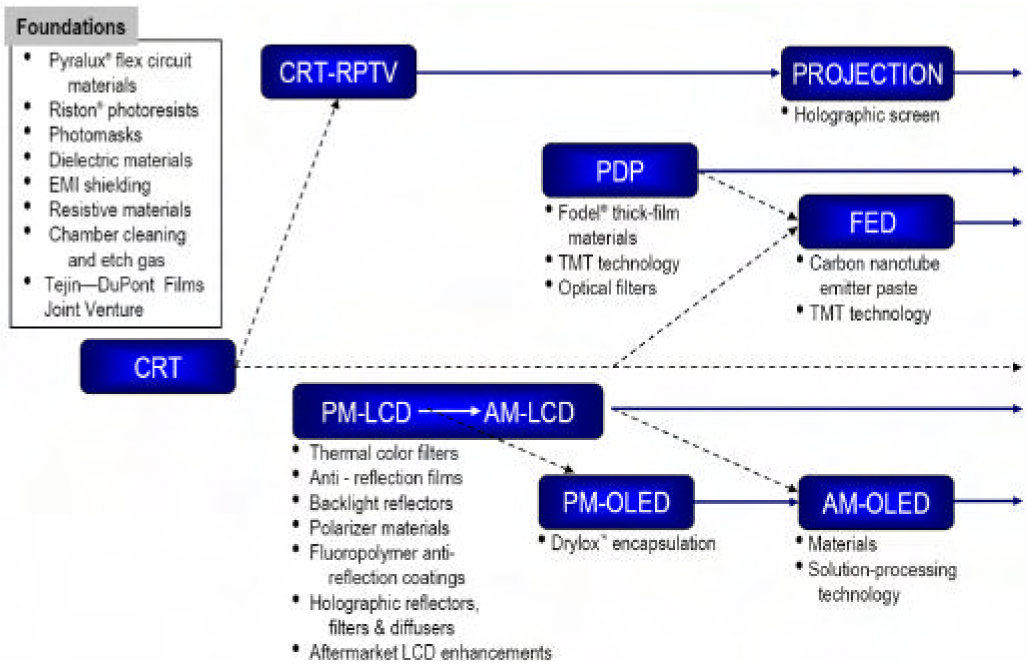
With regard to flexible displays, several companies have already showcased prototype products using E Ink's technology. Plastic Logic showed off a demonstrator more than three years ago. Polymer Vision recently showed their Readius e-book reader, while Epson has demonstrated various smart label solutions using their SUFLA approach. Most recently, LG.Philips LCD showed a 10.1 inch flexible solution with a steel foil backplane.

Wilcox went on to explain E Ink's open system approach – where they intend to make their film available to everyone. He emphasized that one of the advantages of E Ink's technology is that about 80% of the components used with E Ink are common to TFT LCDs. The backplane, bottom glass, and row drivers can be identical to TFT LCD, while the column drivers and assembly are quite similar. The FPL layer simplifies the component count significantly, replacing the top sheet glass, polarizer films, spacers, liquid crystal, rubbing step, filling step, and the backlight assembly – enabling a simpler and less-expensive production process as compared to TFT LCDs. In addition to providing a simpler production model that is common to the existing TFT LCD infrastructure, E Ink's open business model is easy to integrate across many display applications, enabling numerous different applications to support the technology with relative ease. Wilcox envisaged a supply chain that included partners such as Toppan (to coat/convert the basic pigments from E Ink into the FPL layer), cell and module assembly by PrimeView and perhaps other TFT LCD manufacturers using specialty device drivers from Micronix, and then incorporated by device integrators such as Sony.

Wilcox concluded by suggesting that there are still numerous areas where many companies can participate in the development of EPD solutions. From a materials perspective, he highlighted needs for various surface films and coatings (anti-glare, anti-reflective, anti-scratch, and moisture barrier), flexible transparent conductors, and low-cost, high-resolution patterned flex circuits. In the area of module assembly, he pointed to needs for large-area frontlights, flexible frontlights, flexible color filters, flexible touchscreens, and chip-on-flex development. In the area of EPD electronics, he cited needs for drivers with DC conversion, variable voltage drivers, power ICs with five levels, and host processors that support bistable displays.

"Materials Science and Patterning Technologies for Displays": *David Flattery*, Director of Operations, **DuPont Displays.** Mr. Flattery briefly outlined the history of materials development done at DuPont over the past two centuries. For the first century, the company was primarily involved in the explosives industry and for the past century has been focused on the chemical and energy industries. For the coming century, DuPont has identified five areas where the company intends to invest its energies, including electronics and displays, performance materials, agriculture and nutrition, safety and protection, and coatings and color. At least three of these areas of focus for DuPont are expected to impact the displays industry.

As a sub-component manufacturer, many people in the displays industry are not aware of the many areas where DuPont has developed products, in many cases where they are leaders in the industry. The following chart gives an idea of the numerous display-related activities in which Dupont is involved:



Flattery discussed developments related to DuPont's Fodel technology (for high-resolution PDPs and CNT pastes). He also discussed DuPont's efforts related to thermally imaged color filters. The thermal color filter system has several benefits that will eventually transition from rigid glass to flexible substrates. Because it's a completely dry imaging process, no photomasks are needed, liquid handling is unnecessary, there are no nozzles or slots to clog, all of which contribute to increased uptime, higher throughput, and less costly equipment. As such, there are fewer process steps, that enable a simpler pattern job changeover, and that requires less cleanroom space. Additionally, the process is relatively insensitive to the type of substrate – most flexible substrates should work fine using DuPont's thermal imaging process for laying down color filters.

Flattery also discussed DuPont's development in the area of OLEDs. In this area, Flattery argued that "the key to making OLEDs a low-cost reality is a solution-processed printing approach". In reviewing OLEDs, he identified four major challenges. 1) Lifetime still needs to be improved to meet commercial specifications. 2) Patterning processes need to be scalable, cost-effective and high-yield. 3) Encapsulation technologies must enable long storage lifetimes at a low cost and with design flexibility. 4) The TFT backplane must be manufacturable using the existing LCD technology and infrastructure. DuPont is working on solutions for the first three problem areas, where they are combining materials and process development efforts. Flattery expressed considerable confidence that DuPont would find solutions (with its partners) in association with the first e problems, and that the industry as a whole will identify solutions for OLEDs in the near future.

"The Plastic Electronics Revolution: from Research and Invention to Customers and Products": *Stuart Evans,* CEO, **Plastic Logic.** Evans identified the goals of Plastic Logic as being to create new technologies for printing electronics so that display and circuit manufacturers can "escape the constraints of mask alignment and high temperature processing". He foresees that Plastic Logic will help to enable new markets for flexible displays and other applications and promote rapid market growth by licensing the company's device and process technologies to display and printing companies in high volume market segments.

Evans was encouraged that numerous sources are increasingly verifying the market potential for flexible display technologies. In 2005, the following forecasts were published:

- **iSuppli:** flexible display TAM of $22 billion by 2009, noting there are still major issues related to manufacturing ramp-up
- **IDTechEX**: plastic electronics $30 billion by 2015; up to $250 billion by 2025
- **Samsung:** $9.7 billion revenues from flexible displays by 2010 – based on display modules, not just backplanes
- **Intertech:** 40% (by area of flat panel displays will be flexible)
- **NanoMarkets:** displays will be 46% of $5.8 billion plastic electronics market by 2009. Total market will grow to $23.5 billion by 2012.

Of this large market opportunity, Evans discussed two areas of particular interest to Plastic Logic. First, they see a sizable future for electronic shelf labels (ESLs) and other store-based promotional signage. According to Evans, the next generation will be defined by high readability of e-paper ESLs, initially segment driven, but eventually active matrix. He estimated that ESLs will grow quickly to represent a market opportunity of about $7.8 billion per annum.

Plastic Logic sees the ESL market growing rapidly, first as segment displays, but later as active matrix displays

In addition to ESLs, Evans identified e-book readers as another major opportunity for plastic displays. Beyond just books, however, the demand for electronic readers may well come largely from the newspaper industry. Evans identified that particularly in Asia, the market for newspapers is vibrant – much larger than in the West – and that demand for e-newspapers is likely to come from Asia. Of the top 100 newspapers, the combination Japan, China, India, South Korea, Taiwan, and Thailand represent 80% of worldwide circulation. The primary limiter to electronic readers, to this point, has been the difficulty of creating a flexible and affordable backplane.

Concept e-newspaper from IBM – such concepts limited by a lack of affordable flexible substrates

Evans identified several advantages associated with Plastic Logic's development of solutions for the plastic electronics market. In particularly, he identified the advantage of being a first-mover, leading the market with the world's first prototype line for flexible e-paper displays. He also identified that Plastic Logic has a "stunning mixture of engineering and science" both in-house and in connection with several world-class universities. Evans further described how Plastic Logic's technology is well-positioned to move to large area flexible electronics solutions. Moreover, the rate of innovation is accelerating as the company's core technologies are brought to market.

New developments at Plastic Logic include such breakthroughs as self-aligned printing for 60 nm transistors, printing of both p-type and n-type transistors (enabling CMOS technology), a fundamental invention that combines polymer frontplane and backplanes, enabling all-polymer displays, and various new high-performance material systems including some novel ideas about touch-enabled displays and narrow-web roll-to-roll processing.

Evans also highlighted Plastic Logic's participation in the UK government's support of the next-generation production of plastic electronics with investments into the new Direct Write Technology Center in north-east England. Such government support is expected to help generate additional leadership within the UK in the area of flexible electronics.

Plastic Logic's narrow-web roll-to-roll processing is progressing (and will eliminate so much human interaction).

"Status and Potential for Phosphorescent OLED Technology": *Mike Hack*, Vice President Strategic Product Development, **Universal Display Corporation.** Hack outlined the reasons behind UDC's development of phosphorescent OLED technology (as opposed to fluorescent OLEDs), citing several advantages particularly with regard to quantum efficiency – which results in advantages associated with lifetimes and power efficiency. Hack also reviewed progress that UDC has made with regard to improved red, green, and blue phosphor lifetimes, showing continual improvements, and although there are still issues associated with blue lifetimes and luminous efficiency, recent developments are bringing PHOLEDs closer and closer to the requirements of some applications.

Hack identified that PHOLEDs provide a substantial advantage to the enabling of amorphous silicon backplanes (rather than low-temperature poly-silicon) in efforts to affordably bring AMOLED to market. Because lower temperatures can be used to process PHOLEDs, threshold voltages can be reduced. By using a-Si backplanes, it's expected that AMOLED can achieve higher production yields as a result of fewer mask steps, and larger substrates, (due to fab investments in a-Si technologies).

While Hack did not spend time discussing flexible displays, UDC has developed flexible devices using their PHOLED technology. Hack showcased a broad continuum of developments supported by PHOLED, as indicated in the below roadmap timeline.

9.2: The Potential Application of Electronic Paper

Amy Chen
SiPix Imaging, California

Chen gave an overview and reported progress on the SiPix EPD electronic paper technologies and products. She pointed out that each display technology has strengths and weaknesses and that there is no single display technology can meet all of the requireme nts of various applications. In general, applications can be categorized as entertainment-centric and information-centric although the two applications will merge to some extent over time, she said. SiPix believes that electronic paper at this time is more suitable for information-centric applications.

These can be divided into commercial and consumer applications. For commercial applications, it will include e-sign, message boards, white boards, and ESL (electronic shelf label)/POP (point of purchase). For consumer applications, it will include products like e-book, e-newspaper, IC cards, PDAs, cell phones, USB drives, toys, etc.

The characteristics of electronic paper should include some or all of the following, said Chen:-

- Bi-stability (no power needed for image retention)
- Reflective type display (no backlight, low power consumption)
- High contrast ratio
- Low material and manufacturing cost
- Low cost production with roll-to-roll automation capability
- Multiple colors in one display panel
- Wide viewing angle
- Ambient/sunlight readable
- Thin and lightweight
- Flexible, format flexible
- Durable
- Large area

ESL/POP: A low power display which can be powered by battery is required since most retail outlets do not have AC power. The bi-stability feature of electronic paper is preferable for this application. The display should have good contrast and viewing angle that can be viewed from about 20 feet away. Monochrome color will be accepted for the ESL application, but multi-color will be required for POP signs. In a POP design, it would be beneficial to have a design that combines electronic paper with traditional media, such as paper, plastics, and wood.

IC card: The IC card application requires a display which can be packed in a 0.76 mm thickness package. It will need a flexible, bendable display since it could be bent or dropped. Low power consumption is needed so that a thin battery can be used. An anti-scratch feature would be a plus. The IC card with display features can be extended for prepaid cards, telephone cards, subway cards, bank cards, membership cards, etc. For example, an IC card can show a one-time password to add security features.

e-sign: The e-sign application requires a display which is bi-stable and can be connected to become large form factor. Good contrast is needed so that people can view it from large distances and from various angles. Response time in this application is less of a factor. Multi-color or area color to show good images is preferred. Besides the horizontal market for corporations, the vertical market will need a variety of e-sign products for industrial/manufacturing, retail stores/shopping malls/service centers, convention centers/trade shows, restaurants, transit facilities and networks, hotels, health clubs, sports arenas and venues, medical facilities, museums and banks.

Currently, various display products, are serving the e-sign market, such as LEDs, plasma and TFT LCDs. But EPD will enter into the e-sign market, Chen believes, by providing the features of large form factor, format flexibility, low power consumption, and good bi-stability. For outdoor e-sign applications, the operational temperature range and the performance stability of UV and light exposure need to be considered. Also, they will need a light source for night use.

e-book: SiPix places importance on having a rugged design for student use, so a flexible backplane is preferred. A glass backplane is not suitable for the student e-book market. This market will grow, says SiPix when a flexible, high-resolution dot matrix backplane can be delivered at an affordable price. An e-book using electronic paper does not require a backlight which would be a good feature for long hours of reading. The price of memory cards and wireless chips has dropped significantly which will help fuel the e-book market, Chen said.

Consumer devices: One example will be USB drives with displays to show the remaining memory size. The display should have bi-stability, and be thin and light-weight. A USB device would not have battery in it. Another example could be a device that shows how much steps have been walked. Since users will carry it around, the device needs to be rugged, light-weight and have low power consumption.

9.3: iMoD Displays for Mobile Applications

Gang Xu
Qualcomm MEMS Technologies, California

Qualcomm's iMoD is a reflective display based on micro-electromechanical system (MEMS) technology. The always-on display features low power consumption, high brightness, high color saturation and sunlight viewability, making it suitable for mobile applications. Successful development of the display module requires seamless integration of the core MEMS technology with peripheral technologies such as driver electronics, illumination and packaging.

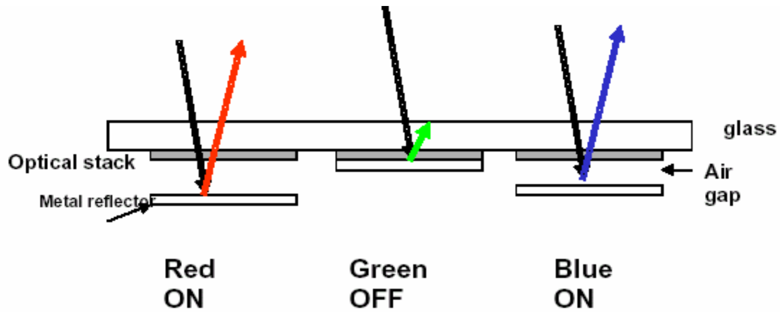


Figure 1: A color iMoD pixel, with R and B in the on state and G in the off state. The air gap decides the color of the subpixel. When the gap is zero, the subpixel is in the black state

The iMoD is a reflective display technology combining MEMS and thin film optics. Before its acquisition by Qualcomm in 2004, Iridigm had been developing this technology. The basics of the iMoD structure and operation are illustrated in *Figure 1*, where a pixel of iMoD with R, G, and B subpixels on a glass substrate is shown. Each of the subpixels has an optical stack with deposited thin films, an air gap and a metal membrane. The membrane is addressed by applying a voltage across the air gap between the membrane and a transparent electrode. For incoming light through the substrate glass onto the device, the optical design is made so that a dark state of low reflectance is achieved when the air gap is collapsed by pushing the membrane to the optical stack, and a reflective color, red, green or blue, is achieved when a designed air gap is maintained.

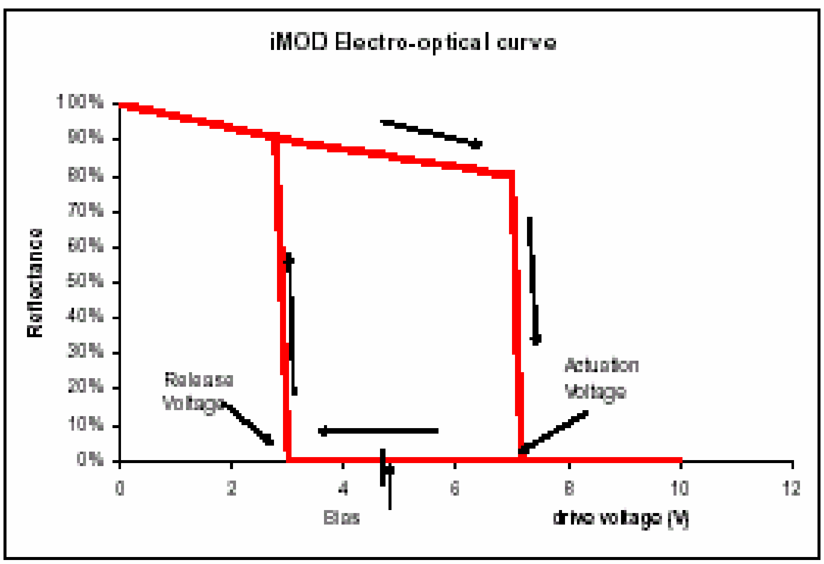


Figure 2: iMoD electro-optical curve

The iMoD is a bistable device, characterized by a hysteresis window on its electro-optical curve, as shown in *Figure 2*. When a bias voltage, set in the middle of the hysteresis window, is applied to the membrane, it may stay in either up or down position, depending on the history. In addressing the iMoD device, a pulse of either high or low voltage larger than the half width of the hysteresis window is superimposed to the bias voltage, to write either a black or bright state to the device, and then the bias voltage is maintained to hold the image.

An iMoD is driven very much like an STN LCD. No active matrix TFT is required, because of the intrinsic bistablility of the device. A pixel is driven by voltage difference between the row and column lines. During each frame the rows are selected by a selection pulse sequentially scanned from the top to bottom. During the selection time of each row, the data for that row is written on column lines, by setting them to either a "low" or "high" voltage level.

Unlike LCD, iMoD requires no polarizer. Therefore, the optical efficiency is very high, the company says. At the reflecting peak the reflectance can be as high as 80-90%. The iMoD device looks much brighter than a reflective or transflective LCD with the backlight off, the company claims. A color iMoD can achieve reflectance of 30% for balanced white color, about twice as bright as a color TFT LCD with backlight off, the company maintains.

The grayscale or color depth for an iMoD can be achieved in the spatial or temporal domains. The response time of the device is in the order of tens of microseconds, at least two orders of magnitude faster than that of a typical TFT LCD. Also the color elements and row and column lines are made on the same substrate, eliminating the need of registering the plate of the color filter with that of the TFT array. These two facts allow iMoD to achieve grayscales by temporal and spatial dithering.

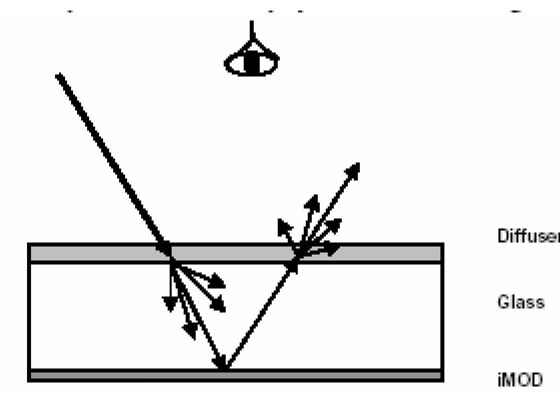


Figure 3: The diffuser diverts light from a point source to all directions

The iMoD array is the core of an iMoD module. But it is typically implemented as a display by using it together with a diffuser, front lighting, packaging and driver electronics. An iMoD array itself is a nearly perfect specular reflector. To view the display in all lighting conditions a diffuser is attached on the front surface of the substrate glass. As shown in *Figure 3*, the diffuser diverts light from a point source to all directions so that the image can be seen by a viewer from the normal direction. But the diffuser could cause image blurring. Choosing a thin substrate and a haze value for the diffuser is crucial to keep the image sharp and to make the display viewable from all angles.

A front light is used when the iMoD module needs to be viewed in very dark conditions. The front light technology developed for reflective LCD can be used for iMoD. Usually an LED is used as the light source. Due to its higher reflectance, an iMoD module requires much less LED power to achieve the same brightness. High reflectance also makes an iMoD viewable under usual room lighting conditions without the need to turn on the front light, the company says. In display modules, the power consumption for lighting usually is much higher than that for the driver. So a larger percentage of power saving of an iMoD module is achieved by reducing the use of lighting.

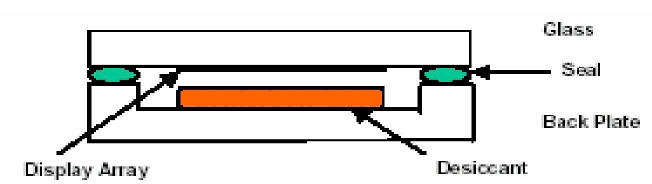


Figure 4: Packaging against mechanical and moisture damage

The packaging of an iMoD is designed to prevent its membrane on the substrate from damage such as mechanical contact and moisture. OLED technology has already developed ways of backplate packaging, such as shown in *Figure 4*, which can be adapted for iMoD use. Compared to an OLED, the iMoD requirements for hermetic sealing are far less strict, Qualcomm says. The iMoD display has been demonstrated using an off-the-shelf STN driver. To maximize the benefits of iMoD, customer drivers should be designed to take advantage of the intrinsic bi-stability of an iMoD device and integrate the drive schemes for gray levels, the company says.