Electrofluidic displays: Fundamental platforms and unique performance attributes

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Abstract — Electrofluidic displays transpose brilliant pigment dispersions between a fluid reservoir of small viewable area and a channel of large viewable area. Recent progress in the technology, a new multi-stable device architecture, and a novel approach for segmented displays that can display pigment without the optical losses of pixel borders is reported. The fundamental aspects of electrofluidics that make it compelling for the next generation of e-paper products is reviewed.

Keywords — *Electronic paper, reflective displays, electrofluidic displays.*
DOI # 10.1889/JSID19.9.608

1 Introduction

Electronic paper (e-Paper)[1] has now demonstrated near-zero-power operation, a flexible or rollable form factor,[2] superior optical contrast in direct sunlight, and even panel integration with a photovoltaic power source.[3] For portable reading applications, many prefer e-Paper devices because of reduced eyestrain[4,5] and unmatched reductions in display and battery weight. As an example, new ergonomic electronic-reader products have been enabled by electrophoretic display technology. Other applications, such as electronic-shelf labels, benefit from low-power operation that permits 5 years of continuous operation without refreshing the batteries.

Despite these major advances, a commercial e-Paper technology with high-reflectance color and gray scale comparable to printed media is still lacking. Furthermore, some of the most promising color e-Paper technologies are unable to provide the speed required for advanced touch interfaces or video media. There are numerous technologies,[1] each with distinct advantages and drawbacks, with no single technology yet providing a complete solution. We argue that fundamentally, and practically, the highest performance e-Paper likely involves several basic principles as shown in Fig. 1. ***First basic principle:*** Based on current data[1] the highest achievable reflectance seems to be based on horizontal colorant transposition. Colorant transposition moves pigment or dyes out of the optical light path, and like paper is independent of polarization or the propagation angle of light. Example technologies include in-plane electrophoretic,[6,7] electrokinetic,[8] electrowetting,[9] and electrofluidic.[10,11] ***Second basic principle:*** Ideally, a technology will use pigments which exhibit the most robust performance. Pigments can be self-diffuse (optically scattering) for inherently wide viewing angle, and generally they provide superior light fastness due to less surface-area exposure to oxygen, light, or other reactive molecules.[12] ***Third basic principle:*** The pigment should be moved along with a moving fluid, not moved through the fluid itself. Pigment movement through a fluid is used in electrophoretic displays and is ~100× slower over similar length scales compared to technologies that move the fluid itself (*e.g.*, like electrowetting or electrofluidic). The speed is so much faster because an applied electric field can be localized to the advancing edge of the fluid (not dropped across a large path for fluid motion). This localization of an applied electric field allows a stronger force. The speed is also faster due to drag forces; moving fluid with pigment inside experiences a drag force only at the external edges of the fluid, whereas moving pigment inside the fluid causes drag at every single moving particle. Typically, electrowetting and electrofluidic control can provide switching velocities of 10 cm/sec (over 100 μm that is ~1 msec).[13] Faster switching speed can also boost reflectance, especially when the frame rate exceeds the pixel switching time (*e.g.*, video-rate displays or large pixels in signage because pigment can be moved further (more compacted) during each display frame. At present, among all the technologies existing for e-Paper,[1] electrofluidic is the only technology satisfying these three fundamental requirements depicted in Fig. 1.

Electrofluidic displays were first reported by the University of Cincinnati and are now commercially pursued by the 2009 spin-out company Gamma Dynamics. In this paper we review the fundamental platforms that now exist for electrofluidic displays. They include the earliest platform reported in 2009,[10] which compacts a pigment dispersion in a small reservoir, a bistable approach reported in 2010,[11] and a platform also reported in 2010 that uses "Laplace Barriers"[14] for simple and ultra-high reflectance segment-style displays. Each technology will be reviewed in terms of its

Extended revised version of a paper presented at the 17th International Display Workshops (IDW '10) held December 1–3, 2010 in Fukuoka, Japan.
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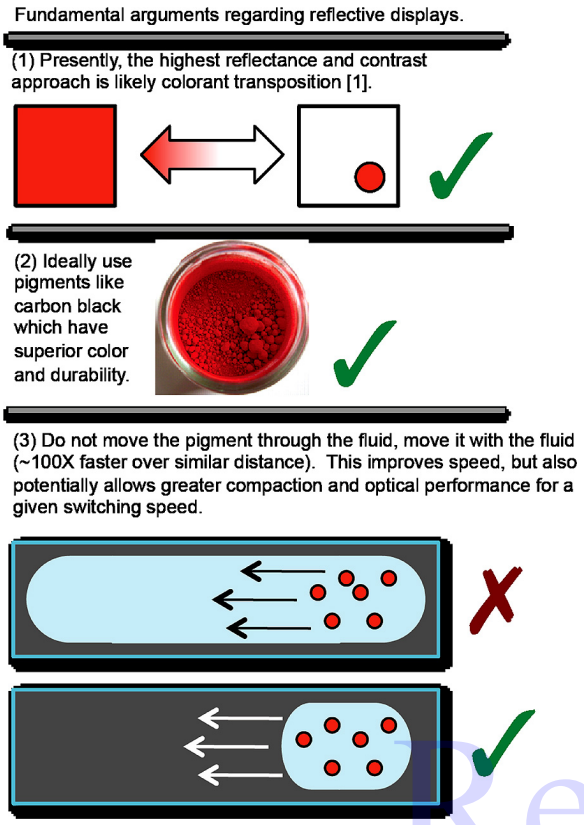


FIGURE 1 — The author's fundamental arguments for reaching the maximum practically achievable performance for e-Paper.

related background, construction, physics, performance, and outlook. Electrofluidic displays now comprise multiple versatile platforms which can arguably satisfy the requirements for the next generation of e-Paper products.

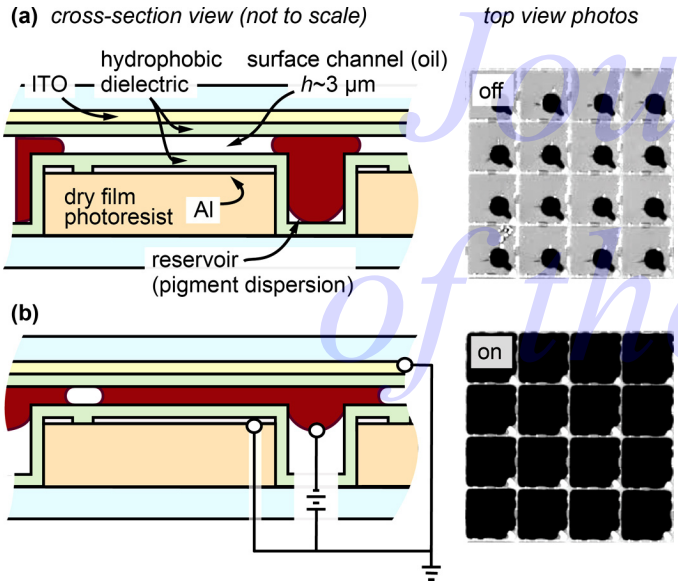


FIGURE 2 — Schematic cross section of (a) OFF and (b) ON electrofluidic display pixels with reservoirs, with photos of pixel operation shown at right.

2 Electrofluidic pixels with reservoirs

2.1 Background

The Cincinnati group first demonstrated electrofluidic displays after several years of work in electrowetting displays. The development for the first electrofluidic displays was originally motivated by a collaboration with Sun Chemical Corp. (subsidiary of DIC), which had interest in applying advanced pigment dispersions to electronic displays. The development was also motivated by Huitema and Touwslager of Polymer Vision (now Winstron), who were seeking video-speed e-Paper technologies that could also satisfy the unique requirements for rollability.

2.2 Device construction and physics

Each electrofluidic pixel shown in Fig. 2(a) consists of two microfluidic features formed in a dry film photoresist (a reservoir that holds a pigment dispersion in less than 5–10% of the visible area) and a horizontal surface channel that without the pixel border comprises 70–90% of the visible area. The top electrowetting plate comprises a transparent In_2O_3:SnO_2 electrode (ITO) and hydrophobic dielectric, such that the surface channel is viewable by the naked eye. The bottom electrowetting plate is non-planar (contains the reservoir) and has a similar electrowetting electrode and hydrophobic dielectric. The electrode can be reflective (aluminum) or also transparent. Diffuse reflection can be enabled by all standard techniques[15] (front diffuser, rear diffuse electrode, transparent pixel and rear diffuser, or self-diffuse pigment dispersion).

The Laplace pressure for the pigment dispersion in the reservoir is determined by $\Delta p_R = 2\gamma_{ci}/\mathrm{R}$, where R is the radius of the reservoir and γ_{ci} is the interfacial tension between the conducting pigment dispersion (c) and insulating oil (i). Because the top channel height is significantly smaller than its horizontal dimensions, and because the Young's angle of the pigment dispersion in oil is ~180°, the Laplace pressure in the top channel can be approximated as $\Delta p_C = 2\gamma_{ci}/h$, where h is the height of top channel. Since $h << \mathrm{R}$, the pigment dispersion favorably occupies the reservoir and is largely hidden from view. When a voltage is applied across the top and bottom electrowetting plates, as shown in Fig. 2(b), the pigment dispersion contact angle reduces according to electrowetting:

$$\cos\theta_V = \frac{\varepsilon \cdot V^2}{\gamma_{ci} \cdot 2d} - 1, \qquad (1)$$

where the electrowetted contact angle (θ_V) is a function of the hydrophobic dielectric capacitance per unit area (ε/d) and the applied DC voltage or AC RMS voltage (V) across each hydrophobic dielectric. The result is a competition between Laplace pressure in the channel and electromechanical pressure caused by electrowetting:

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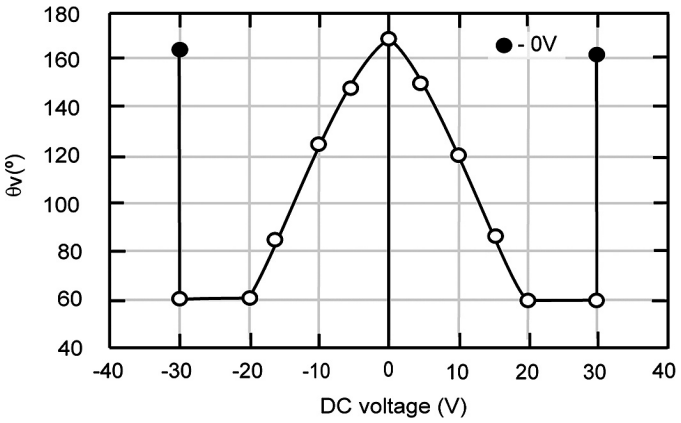


FIGURE 3 — Contact angle change *vs.* driving voltage for example low-voltage dielectrics[17] used in electrofluidic displays. The Young's angle is actually 180°, but imaging resolution limits the measurable Young's angle to ~170°.

$$\Delta p \approx \frac{2\gamma_{ci}}{h} - \frac{\varepsilon \cdot V^2}{h \cdot d}. \qquad (2)$$

The pigment dispersion advances into the channel as soon as the electromechanical pressure is greater than the Laplace pressure. This threshold is typically near $\theta_V \sim 90°$ (see Fig. 3). When the voltage is removed, θ_V returns to 180° and the Laplace pressure causes the pigment dispersion to rapidly recoil back into the reservoir.

2.3 Switching voltages/speed

Voltage requirements range from <10 V for thin inorganic dielectrics (Si_3N_4, Al_2O_3) coated with fluoropolymer to tens of volts for organic Parylene C or HT dielectrics. In general, the challenge is to make the dielectric as thin as possible to increase electrical capacitance, while maintaining reliable electrical insulation. Environmentally compliant pigment dispersions[16] can now provide an operating range from –30 to +60°C and a storage range from –40°C to +80°C. These same dispersions also provide switching speeds on the order of ~20–30 msec for 150 × 150 μm^2 pixels. Far faster speeds are possible through optimization of viscosity, surface tension, and channel dimensions.[10]

2.4 Discussion

Currently, Gamma Dynamics is developing more sophisticated active-matrix prototypes. Electrofluidic displays are compatible with numerous color systems including RGBW color filtering, fluorescent enhanced RGBW, bi-primary, and two-layered CMY color systems.[1] The electrofluidic displays with reservoirs are suited well for applications that require fast pixel response, high reflectance, and possibly transparent or transflective display applications.

3 Multi-stable electrofluidic pixels

3.1 Background

e-Paper pixels that can retain their gray-scale state without electrical power are attractive in terms of both reduced power consumption and increased operation lifetime (less voltage cycles). Although electrofluidic display with reservoirs are currently unable to provide bistable operation, two bistable forms of the electrofluidic display were conceived by the University of Cincinnati several years prior to first publication in 2010.[11] Despite the opportunity for bistability, intense research and development on these new structures did not start until a manufacturable fabrication process was available. Initial fabrication was enabled by cooperation with DuPont Corporation with their new PerMX dry-film photoresist, which allows creation of a multi-layered electrofluidic structure.

3.2 Device construction and physics

As illustrated in Fig. 4(a), the multi-stable pixel is constructed as follows. The bottom and top substrates both support electrowetting plates, similar to the device described for electrofluidic pixels with reservoirs. In between these electrowetting plates, three layers of Dupont PerMX™ dry-film photoresist are hot-roll laminated and photolithography patterned to form an upper and lower channel of equal dimensions. On the middle PerMX layer, a reflective aluminum ground electrode is coated. All surfaces of the pixel are

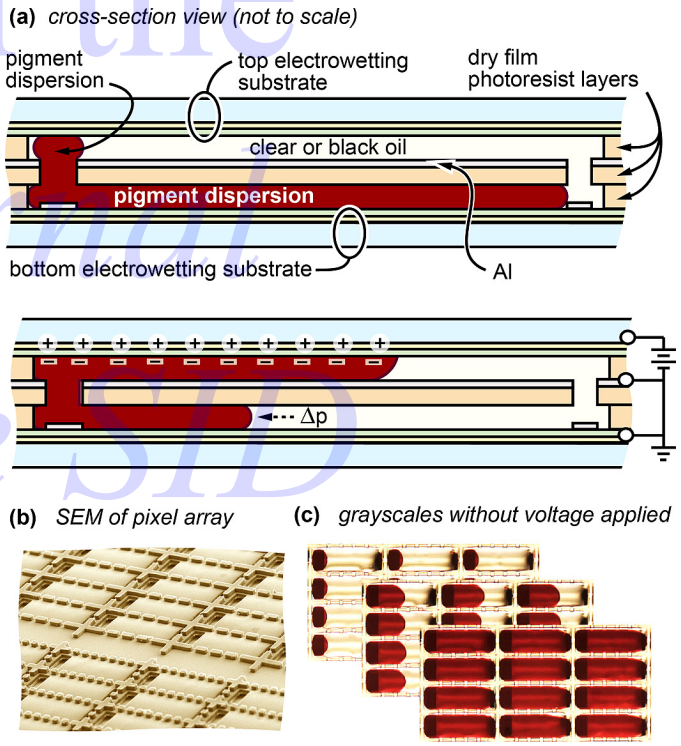


FIGURE 4 — Multi-stable pixels: (a) diagrams, (b) SEM photograph of a pixel array, and (c) gray-scale operation photos.

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then coated with a very thin hydrophobic polymer and the pixels filled with oil and pigment dispersion. A SEM photograph of a 450 × 150-μm^2 pixel array is shown in Fig. 4(b) (top substrate not included). Since the geometries of the two channels are nearly identical, without voltage, the Laplace pressures in each channel are equal to $\Delta p_0 \cong 2\gamma_{ci}/h$, where h is both the top-channel and bottom-channel heights. Therefore, no pressure imbalance is exerted onto the pigment dispersion without voltage. Typical channel heights are ~20 μm and a 10% channel-height variation is acceptable for maintaining bistability. When voltage is applied to one of the channels, electromechanical pressure pulls pigment dispersion into that channel. By removing all voltages or applying an equal voltage to both channels, the pressures will be balanced, resulting in a stable gray-scale position for the pigment dispersion. Theoretically, this multiple stable mechanism is able to display any arbitrary gray-scale state [Fig. 4(c)], and gray-scale states have been shown to be stable for months (essentially, infinitely stable with time).

3.3 Measured pixel results

The reported multi-stable electrofluidic pixel (450-μm length, 20-μm height) switching speed was measured as ~170 msec. It is slower than the reservoir pixels mainly because of the relatively larger pixel size and single electrowetting plate drive. To achieve video speed, as discussed in the previous section, scaling down the pixel length is the most reasonable approach. The speed scales as L^2, where L is the pixel length, because both fluid drag force and distance traveled scale with L. Therefore, video operation is feasible. Multi-stable pixels exhibit good optical performance. The measured white-state reflectance is as high as 75% for latest-generation versions of these two-channel devices. This 75% reflectivity is diffuse (specular reflection excluded[1]) which is among the highest white-state performance reported for any e-Paper technology.

3.4 Discussion

With high reflectivity and zero-power gray-scale operation, multi-stable electrofluidic pixels can serve numerous e-Paper applications. The fabrication process is now being further simplified by researchers at the University of Cincinnati and Gamma Dynamics, such that low-cost applications can also be served (electronic shelf labels and billboard signage).

4 Segmented electrofluidic pixels with no pixel boundaries (Laplace barriers)

4.1 Background

The University of Cincinnati has recently demonstrated[14] another approach to achieve a stable image display without power consumption. In this approach, fluid is moved horizontally through a single channel. This is similar in some respects to droplet-driven displays developed by ADT. ADT moves a colored droplet in hundreds of milliseconds to seconds between two horizontally confined reservoirs.[18] The ADT system is binary and stable without voltage.

The Laplace barrier approach developed by the University Cincinnati provides a highly unique set of capabilities. Firstly, fluids can be moved in any direction and formed into any shape (not limited by confining pixelation or reservoirs). Secondly, because there are no pixel walls, optical performance can reach new record levels for e-Paper. Thirdly, the most advanced designs allow >75% open channel area and fluid velocities of >5 cm/sec (~2 msec over a 100-μm distance). Fourthly, fluids can be split and merged as postulated for a predecessor version of the technology developed for lab-on-chip.[19]

4.2 Device construction and physics

The Laplace barriers are constructed of arrayed posts or ridges. The posts/ridges impart Laplace pressure to confine (geometrically stabilize) the fluid, but the Laplace pressure is also small enough such that the barriers are porous to

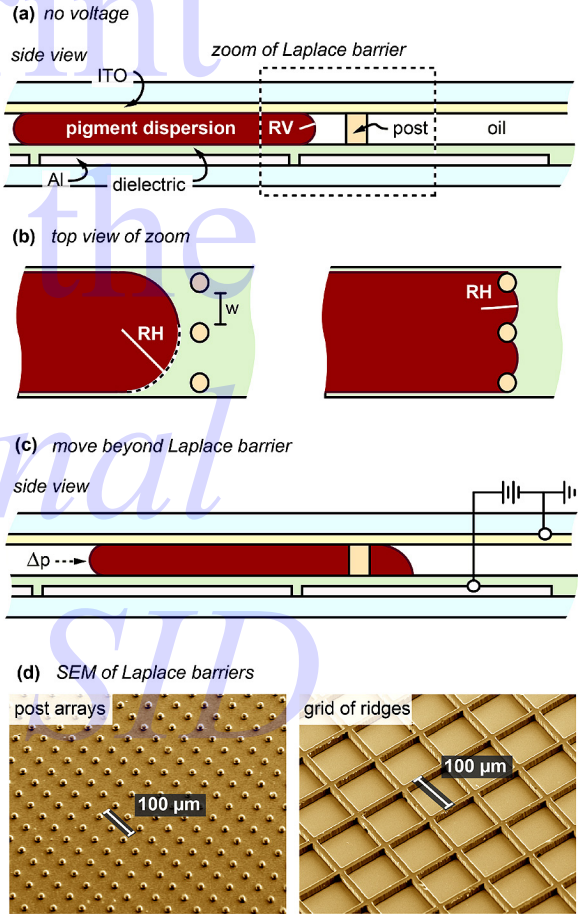


FIGURE 5 — Operation with Laplace barriers: (a) pigment dispersion overlaps with electrode; (b) voltage applied but fluid still stabilized by the Laplace barrier; (c) applying voltage above the threshold voltage and move fluid beyond the Laplace barrier. SEM photos of horizontal and vertical Laplace barriers are shown in (d).

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electrofluidic control. An example post-version of the Laplace barriers is extremely simple to fabricate (requires an inexpensive top substrate that is microreplicated and ITO coated, and simple bottom patterned ITO substrate with a hydrophobic dielectric).

The physics for the post-version of Laplace barriers is explained here (Fig. 5), and ridge versions are explained in detail elsewhere.[14] To move the pigment dispersion forward, voltage is applied to the electrode that has a partial overlapping area with the pigment dispersion. For the post version of Laplace barriers, the horizontal radius of curvature R_H at the front end of the pigment dispersion induces a threshold pressure for forward movement. Once a voltage is applied beyond this threshold, pigment dispersion moves forward rapidly (almost as though no Laplace barriers were in the path of fluid propagation). When voltage is removed, the Laplace barrier then stabilizes the fluid in any desired geometry (stars, numbers, and other shapes have been demonstrated).

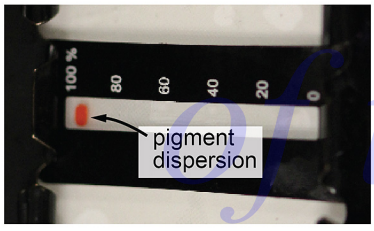
4.3 Measured pixel results

A simple USB memory drive indicator demo is shown in Fig. 6. A perfect rectangular shape is achieved after the fluid is moved from one segmented electrode to another. The reflectivity of Laplace barrier device with black pigment dispersion is shown in Fig. 7. The specular excluded reflectance is close to 80% and the contrast ratio is higher than 50:1. This performance is as good as print on paper.

4.4 Discussion

Although these segment-driven electrofluidic displays using Laplace barriers are not intended for high-information-content displays, they are particularly compelling for symbol, alphanumeric, or other lower-information-content applications. The switching speeds are also fast enough for displays

(a) *electrofluidics demo using Laplace barriers*



(b) *zoom in pigment dispersion movement*

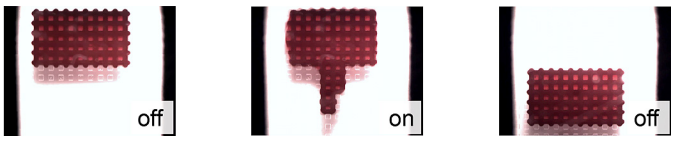


FIGURE 6 — Photographs of electrofluidic devices using Laplace barriers.

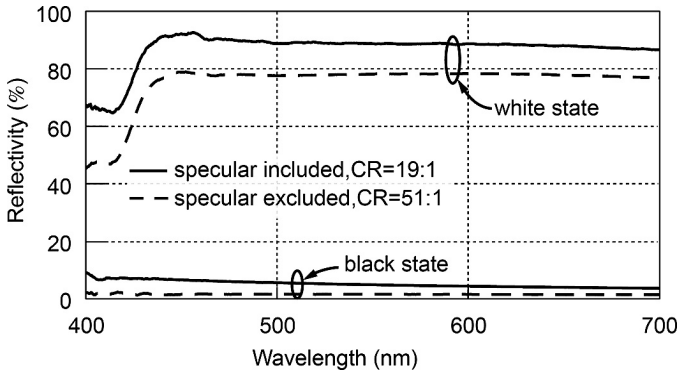


FIGURE 7 — Reflectivity of Laplace barrier devices with black pigment dispersions.

where the user interacts with the display (appliances, for example). Fluid geometries can be simple characters such that applications such as electronic shelf labels are also fully feasible. The combination of high optical performance and low cost construction is promising for many low-information-content uses.

5 Summary

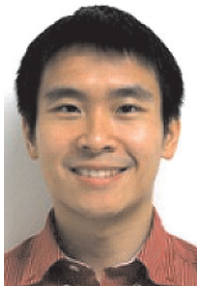
We have reported recent progress in electrofluidic displays, including a new multi-stable device architecture and a novel approach for segmented displays that provides "perfect" e-Paper performance. The capability set for electrofluidic displays is now rapidly expanding to satisfy a variety of potential applications ranging from e-Readers, to electronic shelf labels, even to applications such as simple storage level indicators on USB flash drives.

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Steven Smith is currently the Sr. Process Engineer for Gamma Dynamics. He has been involved with micro- and nano-fabrication processing for the last 35 years, with experience in both manufacturing and R&D environments. His areas of interest include semiconductors, MEMS, sensors, microfluidics, and display technologies. He is the recipient of 11 U.S. patents, over 30 publications, and numerous engineering awards. Professional affiliations include membership in the Materials Research Society and ASM International. Academic studies include Business Administration at SUNY-Canton and Chemical Engineering at Arizona State University.



John Rudolph recently co-founded the Cincinnati-based technology startup, Gamma Dynamics. Previously, he worked for Corning Incorporated in positions involving product and technology development and business management. He has been awarded six patents and has participated as a director in three technology-based companies. He has been active at the Society of Information Display (SID) and chaired the Projection Display subcommittee. He holds a Master of Science (SM) in management from MIT's Sloan School of Management and a Bachelor of Chemical Engineering from the University of Delaware.

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