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Microfluidics for Electronic Paper-like Displays

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Displays are ubiquitous in modern life, and there is a growing need to develop active, full color, video-rate reflective displays that perform well in high-light conditions. The core of display technology is to generate or manipulate light in the visible wavelength. Colored fluids or fluids with particles can be used to tune light intensity (greyscale) or wavelength (colors) of reflective displays by different actuation methods. Microfluidic technology plays an increasing role in fluidic manipulation in microscale devices used in display area. In this article, we will review microfluidic technologies based on different actuation methods used for display applications: pressure-driven flow, electrophoresis, electroosmosis, electrowetting, magnetic-driven flow, and cell-actuation principles.

1. Introduction

Electronic displays are output devices for presentation of information for visual reception. They play an extremely important role in our daily lives. Although people receive information via different senses – touch, taste, smell, aural and visual, it has been shown that more than 80% of information is received visually, and vision is the fastest among all senses.[1] Information such as text, image and video can all be processed and presented by a display device. Televisions, computers, mobile phones, electronic readers, electrical advertisement banners, navigation devices, digital watches and cameras all contain display parts.

Since electronic displays are a ubiquitous feature in modern society; and they constitute a huge business area.[2, 3] Nevertheless, most electronic displays currently is in use are emissive, and it is generally agreed that the mismatch in luminance between such displays and ambient lighting is a source of eyestrain when displays are used for long periods. It is therefore sensible to develop *reflective* display technologies which utilize ambient light. The most used and one of the oldest reflective (static) displays is ink-on-paper. Such displays are superior with respect to readability (particularly in high light conditions), color range, viewing angle and flexibility, and are based on the high contrast between (mostly white) paper and dark colored ink (liquid containing pigments or dyes). As new microfluidic technologies have evolved, we now can deposit and confine this ink in small areas (dots, pixels or segments) and control it to show the information on-demand via externally applied forces, for instance electrical fields, creating so-called "electronic paper-like displays". There is substantial effort worldwide to develop electronic paper-like display that combines the desirable properties of an electronic display with the natural advantages of ink-on-paper. While static ink-on-paper is the technique for traditional paper, dynamically actuated colored-fluid-on-active-substrates is the necessary technology for "paper-like" electronic displays which would satisfy the requirements for both interactive

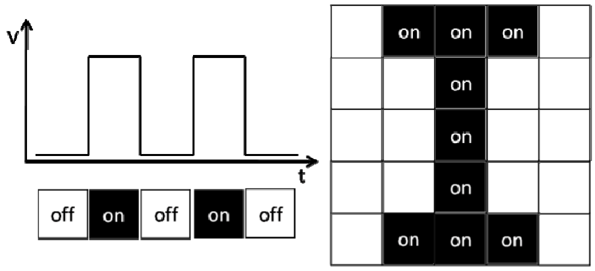

Fig. 1. Schematic drawing of the digital display principle. Left: top is the curve of driving signal and bottom is the sketch of frontplane material showing white and black fluids driven by signal to switch on and off, respectively. Right: a letter "I" is been showing in black by switching on the corresponding pixels or segments.

digital information and paper quality.

A common display is basically bi-level in nature with individual display pixels, all of the same sizes, arranged in a regular array.[4] Displays can present information like text, images or videos in color (visible light) by activating pixels and segments, as shown in Fig. 1. In principle, the display can be controlled via signals, for instance electrical signals, which can activate pixels or segments to present content. Each pixel or segment is aligned and controlled by a display driver IC which can transfer the electrical signal to the materials in the pixel to show the desired color or light intensity. Technologies which can generate, switch or tune light could be potentially applied in display area.

Liquid crystal displays have clearly become the dominant display technology in the last few decades. One may ask why this is the case and what factors contributed to this dominance, which could hardly have been predicted by even the most ardent enthusiast in the early 70's when the first monochrome segmented LCD products emerged for digital watches and calculators. There are many key lessons for new display technologies, in particular those also utilising fluids, to negotiate the challenging path from R&D to manufactured products. The success of LCD has surprisingly little to do with the intrinsic electro-optic efficiency of the liquid crystal switch which was, and remains, extremely low (<10%). Clearly other factors played a role. Ease of manufacturing utilising low-cost solution processing was one of the key factors. The existence of small size products as carriers for the technology, where yield issues are not so critical, helped the fledgling technology. The role of engineering capability and work practices also played a role. This influence still remains today long after the bulk of production activity has been shifted. When a large community of interest builds around a technology, including material suppliers, equipment suppliers and high volume manufacturers, an impetus that is almost unstoppably drives production and performance improvement. It is entirely plausible that microfluidic display technologies such as those reviewed in this publication, that are differentiated from LCD's in terms of electro-optic performance and efficiency, could adopt a similar industrialisation path to that taken by LCD. The key factor will be to identify small-format products to establish any new technology quickly and cost effectively.

An information display device is usually comprised of two basic components – the electrical backplane and the optical frontplane. The electrical backplane is typically a transparent and segmented electrode material (e.g. Indium Tin Oxide (ITO)) or a Thin Film Transistor (TFT) array in the case of a higher information content display. Liquid crystal (LC) materials are the most commonly used optical frontplane materials. Recently, alternative frontplane materials have emerged and those based on microfluidics are the subject of this review. For paper-like display usage, a fluid acts as dispersion medium, being widely available (in nature or by synthesis), easily colored (by dyes or particles), freely tunable (in viscosity, interfacial tension, polarity and so on), diversely actuated (by electric field, magnetic field, pressure, heating or acoustic field), and truly flexible which makes it printable for real paper-like displays. At the microscale, the specific surface area is high and interfacial tension becomes dominant creating opportunities for display applications, such as reduction of inertial and gravitational effects.

In the field of microfluidics, over the past decades a wide variety of actuation methods have been discovered and developed that can be used to actuate colorant or colored particles to move through a fluid or a colored fluid to move in a microscale device providing optical changes in pixels, making this technology very well-suited for display applications. In this article, we review microfluidic display technologies based on different fluidic actuation methodologies, including pressure-driven flow, electrokinetic flow (electrophoresis and electroosmosis), electrowetting, magnetic-driven flow and cell-actuation. The overview of some other e-paper technologies and their current technological and commercial status could be found in other review articles.[2, 5]

2. Microfluidic display technologies

2.1 Pressure-driven microfluidic display (PDD)

For control of fluidic flow in microfluidic devices, pressure-driven flow is still the most popular way, currently being widely using for microfluidics and Lab-on-a-Chip study.[6] Recently, Whitesides et al has demonstrated a microfluidic display based on pressure driven microchannel fluidic flow, for which, the microchannel color can be changed by pumping different colored fluids via connected fluidic tubes. The flexible device they created, as shown in Fig. 2, could mimic the color-changing abilities of animals such as cephalopods by changing the color, contrast, pattern and apparent shape.[7]

Based on the same fluidic pumping principle, there have been several patents describing pressure-driven microfluidic display apparatus responsive to an image file for displaying a plurality of colored pixels. The working mechanism is shown in Fig. 3. Each pixel is connected to at least one fluid chamber via microchannels for displaying one color. A computer controls the microfluidic pumps corresponding to a particular pixel of the image file for selectively controlling the fluid flow to the chamber for selectively displaying either the first or second colors or a fraction of each color thereof. The rapidly developed microfluidic large-scale integration technology makes this technology available to realize display devices.[8-10]

Pressure-driven fluidic flow in a microscale channel can be simply described by Poiseuille's law as:

$$Q = \int v dA \approx \frac{\Delta P}{R_{hy}}, \tag{1}$$

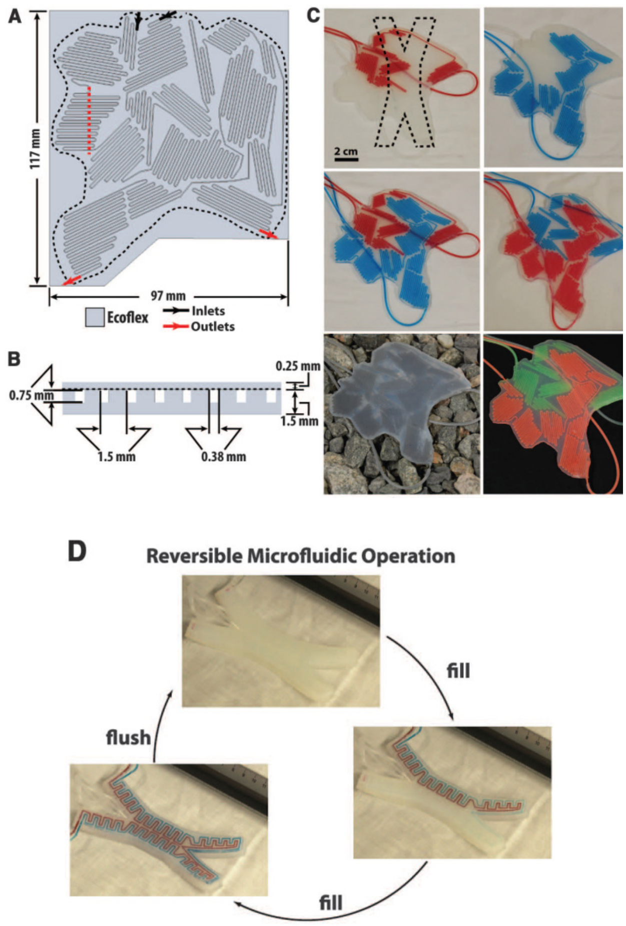

Fig. 2. Design and operation of a color layer based on microfluidics. (A) Schematic of a disruptive color layer comprising two channels. The dotted black line indicates the final shape. (B) Cross-sectional schematic of the region indicated by the dotted red line in (A). (C) Various patterns of coloration generated by filling (or not filling) the channels of a completed color layer with solutions of dye (top four images) and pigment dispersions (bottom two images). The dotted line (top left) shows the outline of a quadrupedal soft robot. (D) Reversible coloration. This color layer design shows the operation of the system and is not intended to camouflage/display the machine. Colored aqueous solutions are pumped by using a syringe. The pumping rate was 2.25 mL/min (channel volume = 0.75 mL). (Reprinted from ref.[7] with permission from AAAS)

where Q is the volume flow rate of fluid, v is the flow velocity, A is the cross-sectional area of microscale channel, ΔP is the pressure difference between two ends of the fluid, R_{hy} is the hydrodynamic flow resistance. It is seen that the flow rate in microscale cells is proportional to applied pressure and inversely proportional to fluidic flow resistance. In principle, the speed of pressure-driven fluidic display depends on the fluidic flow rate filling and empting pixels; the brightness and contrast is mainly

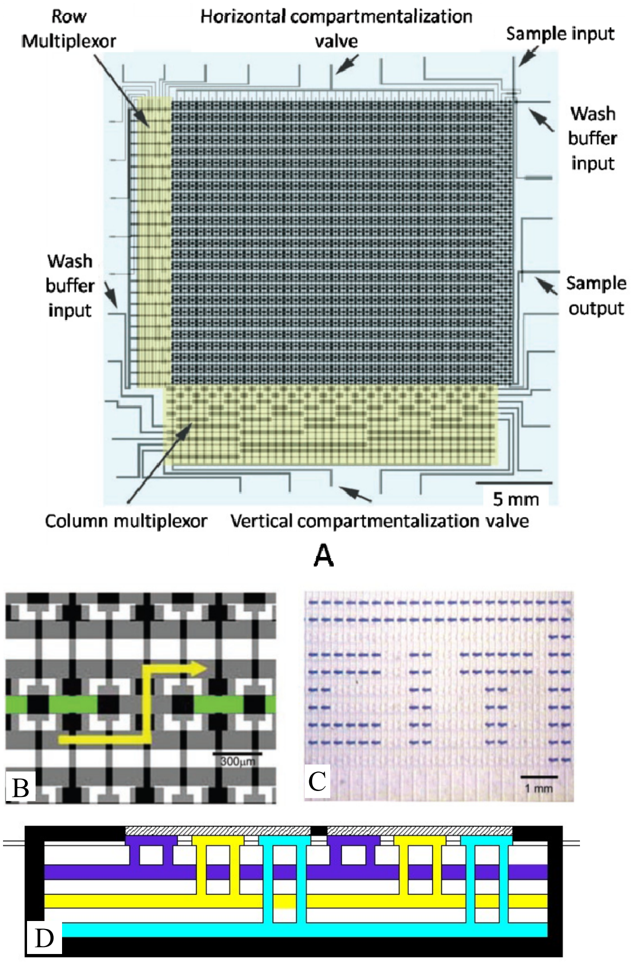

Fig. 3. Pressure-driven microfluidic display working principle and device structure. (**A**) Mask design for the microfluidic device. The chip contains an array of 25 × 40 chambers, each of which has a volume of 250 pL. Each chamber can be individually addressed using the column and row multiplexors. The contents of each memory location can be selectively programmed to be either blue dye (sample input) or water (wash buffer input). (**B**) Purging mechanics for a single chamber within a selected row of the chip. Each row contains three parallel microchannels. A specific chamber is purged as follows: (i) Pressurized fluid is introduced in the purge buffer input. (ii) The row multiplexor directs the fluid to the lower channel of the selected row. (iii) The column multiplexor releases the vertical valves of the chamber, allowing the pressurized fluid to flow through the chamber and purge its contents. (**C**) Demonstration of microfluidic memory display: Individual chambers are selectively purged to spell out "CIT". (D) Cross-sectional view of a pressure-driven microfluidic display structure. (A, B and C are reprinted from ref.[10] with permission from AAAS)

determined by saturation of the colored fluids, and the thickness of the liquid film. However, each display pixel needs to be connected to at least one colored fluidic reservoir. Therefore, except for the back-plane connection, there are still at least three individual layers of fluidic channels plus one layer of materials with pixels, these four layers need to be well aligned and stacked together, as shown in Fig. 3D. Moreover, each fluidic reservoir needs to be connected to at least one pumping resource. This technology therefore might be a good solution for outdoor large screen for displaying slow and simple content; but has not yet matured enough for high resolution (small pixel) and high speed (video rate) displays. Moreover, the power requirements in particular for video rate displays may compare unfavorable with other actuation techniques.

2.2 Electrokinetic displays: electrophoretic display (EFD) and electroosmotic display (EOD)

Up to now, most microfluidic systems rely on one of two manners of fluid transport: pressure-driven or electrokinetic flow including electroosmosis and electrophoresis.[11] Electroosmosis refers to the bulk movement of an aqueous solution past a stationary solid surface, due to an externally applied electric field. It results in a net mass transfer of the aqueous solution. In the limit of small Debye lengths, the Helmholtz-Smoluchowski equation for the electroosmotic velocity is expressed as:

$$U = \frac{\varepsilon \xi_{EO} E_x}{\mu} , \quad (2)$$

where ε is the dielectric constant of the liquid, ξ_{EO} is the zeta potential, E_x is the applied electrical field and μ is the mobility of liquid. Electrophoresis describes the motion of a charged surface submerged in a fluid under the action of an applied electric field. Considering the case of a charged dye molecule or particle, the electrophoretic velocity of the dye or particle is again described by the Helmholtz-Smoluchowski equation,

$$U = \frac{\varepsilon \xi_{EP} E_x}{\mu} . \quad (3)$$

The electrophoretic zeta potential (ξ_{EP}) is a property of the charged dye molecules or particles. Electrophoresis causes movement of charged particles or dye molecules through a stationary solution.

2.2.1 Electrophoretic display (EPD)

The electrophoretic display was first presented in 1973.[12] It was an idea of placing two colored pigments in the glass cavities and controlling the movement of particles for display application. In the following decades, people tried to understand the mechanism and develop a model for commercializing the electrophoretic display.[13-22] The major breakthrough in this field was made in 1998 by Jacobson et al who presenting a novel idea overcoming most of the shortcoming of the electrophoretic display at that moment.[16] They created microcapsules which encapsulated the black and white pigments in a fluid, and controlled the movement of the pigments in fluid in the microcapsule by DC electrical field, which they called electrophoretic ink (E-Ink). Nowadays, the microcapsule based electronic paper display occupies almost 90% of the electronic paper product market. Two popular electrophoretic display structures are microcapsules and microcups, as shown in Fig. 4.

The mechanism of electrophoretic ink can be understood as controlling the movement of micro- or nanoparticles in microfluidic devices: microcapsules or microcups. By changing

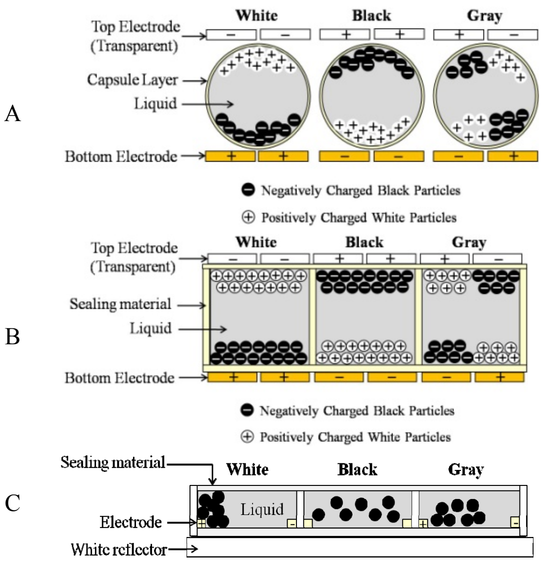

Fig. 4. (A) E-ink microcapsules electrophoretic display structure and working principle; (B) Microcup electrophoretic display structure and working principle; (C) In-plane electrophoretic display structure and working principle.

the charge of electrodes, the particles move up and down which induce black or white images. In order to realize this action, there are several key issues to be considered and solved. First, the black and white particle surfaces need to be oppositely charged which can be realized by core-shell structure [23-27] or surface modification by chemical reaction.[28-31] The second key issue is hetero-coagulation of the particles with opposite charges, which could be solved by providing an extra physical polymeric layer, such as Span80.[32] The third issue for the electrophoretic ink is called bi-stability for which the particles in the liquid do not move or precipitate without driving voltage. This is a very important property for display panel, which means it can show or maintain static images without power. This has also been achieved by modifying the density of both kinds of particles to equal the density of the medium in the microcapsule[24, 26, 33-39]. The fourth one in the E-Ink material is the homogeneity of microcapsules. There are several encapsulation methods which have been used to create the microcapsules.[16, 40-43] However, the microcapsules in the commercialized electrophoretic display panel are still not homogeneous enough, which complicate the driving waveform. Another technology called microcup electrophoretic display by photolithography has been employed to satisfy this requirement,[44] as shown in Fig. 4B. The microcup technology ideally solved the inhomogeneity problem of microcapsules; however, sealing the microcups is difficult.

Simulation studies have been performed to understanding the mechanism behind the electrophoretic system,[45-48] and the E-ink electrophoretic display has been successfully commercialized as a (monochrome) e-book reader. However, there are still factors like the mechanism of particle movement (particle size, size distribution, density and driving voltage and waveform) in the fluid in microcapsules, creation of homogeneous microcapsules, and efficient method of creating and patterning different color microcapsules on the TFT substrate. These issues are directly related to the display driving design, display speed, color gamut and display device size.

When people think about EPD, mostly, they consider the technology of E-Ink which is an up-and-down (vertical) particles movement in capsules technology. Correspondingly, the technology of moving particles left-and-right (horizontal) in-plane (Fig. 3C) has been developed by IBM, Canon, and by Philips[49-51]. The construction of in-plane electrophoretic devices is similar to vertical devices, just with the difference of placing the electrodes within or on the edge of the pixel cells. This structure modification increases the optical performance (70% white reflectance and >10:1 contrast ratio). Gray scale was shown by using multiple electrodes in one pixel cell. The switching time is due to the in-plane distance of particle travel and mobility of particles. The resolution and power consumption is determined by the fluid characteristics and the cell geometries.

A hybrid of vertical and horizontal electrophoretic technology has also been developed by Hewlett-Packard (HP) .[52, 53] By combination of advantages from both vertical and horizontal EPD, this method could maximize the particle compaction which helps to improve the contrast ratio, and speed up the switching speed by reducing electrode gap and pixel size to shorten travel distance for particles. They demonstrated >60% reflectance (brightness L*>80) and 30:1 contrast ratio. A switching speed of <300 ms has been reported at 15 V operation, and 8 gray levels has been shown without necessarily resetting the colorant particles.

EPD commercial products are mainly using the E-Ink technology (E Ink Corporation) founded by Joseph Jacobson from MIT in 1997, and sold to Prime View Int'l Co. Ltd in 2009. Based on E-Ink website information, the newest EPD material named Carta can display 16 grey levels, 50% increase in contrast ratio to 20:1. The speed and color are still challenges for EPD. Color filter and image processing are the basic methods to reach colored display, however, due to the working principle, these two methods will decrease the display brightness considerably. The colored pigments could ideally solve the full-color issue if they could be tuned like print-on-paper approach. However, it is not easy to realize at current stage due to the limitation like particle material, surface charge, encapsulation and confinement in microcapsules[54]. Simple 3-pigment ink has been created by E-Ink which woks similarly to 2-pigment system. The refresh speed of EPD requires further material and waveform development. The refresh speed of a EPD could reach 150 ms by optimizing the impulse signal. Flexible EPD products have been demonstrated for all vertical, horizontal and hybrid electrophoretic displays.

2.2.2 Electroosmotic display (EOD)

Electroosmosis shares a similar equation with electrophoresis, for which liquid can be pumped through a microfluidic channel. Naturally, many materials' surface, used for making microdevices such as glass or silicon, is charged when in contact with aqueous electrolyte. At the microscale, the high surface area of microchannels enhances the electroosmotic flow efficiency. Porous or particle-packed materials can increase the surface area exposed to fluids, which have been used to achieve more efficient electroosmotic flow.[55] Electroosmotic pumps comprising electrically activated electrodes with capillary microchannels could provide the force to move the liquid reagents within the system. The light transmission can be controlled by convergence of liquid along the surface by electroosmotic flow.[56] The hue of the pixel could be tuned by comprising dispersion mixtures of pigment.[57, 58] For the display application, electroosmotic flow can simply work as a micropump to fill and evacuate display pixels[59, 60]. The working devices are similar to pressure-driven microfluidic display in Fig. 2 and 3 by replacing the fluidic filling pump with driving electrodes. For a long period, electroosmotic microfluidic display technology has not yet been widely studied and applied for display application because of its low flow speed and high driving voltage together with electrolysis problem.

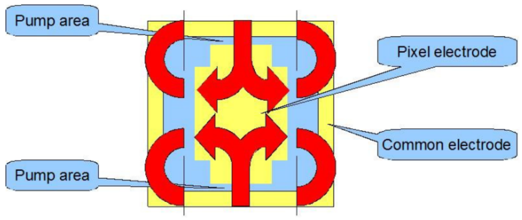

Fig. 5. Schematic pixel geometry of EOD. (Copyright from ref.[61] with permission from SPIE).

Recently, with careful design of electrodes shape and position, a big step has been made by Henzen who demonstrated an EOD prototype in SPIE 2011[61]. The schematic working pixel geometry design is shown in Fig. 5. In the particle suspension, the particles are not transported with respect to the surrounding liquid but rather the particles move together with the liquid. In this EOD, color switch (the motion of liquid coincides with the motion of particles) is obtained by controlling the net charge of the medium is the result of the presence of particles. Ideally, the only electrolyte present should be the particles and their counter-ions; a low dielectric liquid (with minimum electrolyte contamination) is therefore preferred. In this device, the fluid flow takes place on the pixel level. Theoretically, the Debye length needs to be either larger than or comparable to the pixel thickness in order to generate a reasonable EOF coupled with particle motion, a low polar solvent is then still necessary. With the typical speed of around 3 mm/s, 30 ms switch could be expected within 200 um pixels. With carefully combine different parameters of electrode geometry (shape, size, location), surrounding liquid (viscosity, polarity, electrolyte) and particles (material, size, mobility, shape), the EOD might be a solution for higher speed and better in-plane color reflective displays in the future.

EOD technology's promise has been recognized by Henzen and his team, for which the working principle has been proven, paving the way for product development.

2.3 *Electrowetting Display (EWD)*

Pixels of displays are typically hundred micrometer size cells. As we know, when scaling down, interfacial tension becomes more and more dominant over gravity due to the increased specific surface area. Electrowetting is a technology which can change the contact angle between a liquid droplet and a hydrophobic surface when a voltage is applied (Fig. 6A). Electrowetting is therefore an attractive technology for the rapid manipulation of liquids on micrometer scale.[62] Hayes et al first demonstrated the electrowetting-based display (EWD) technology in 2003 (Fig. 6B).[63] The display pixels were fabricated using microtechnology, filled with a drop of colored oil immersed in water. The colored oil sticks to the hydrophobic surface of the pixel bottom forming a thin film without electrical field. By applying a voltage through the water and the electrode underneath the dielectric layer, the oil film contracted to the corner of the pixel because of changing of contact angle. The display can therefore be operated by showing the oil color by spreading the colored oil over the pixel or showing the substrate color by driving the oil into the pixel corner.

Using the same principle but with different display strategy, Heikenfeld et al created a three-dimensional microfluidic structure for displaying fluid by revealing the fluid inside pixels or displaying the substrate color by hiding fluid into a reservoir, as shown in Fig. 6C.[64] Except for the complex fabrication process, this technology exhibits higher reflectance (80%) and improved contrast (50:1) for display application[65].

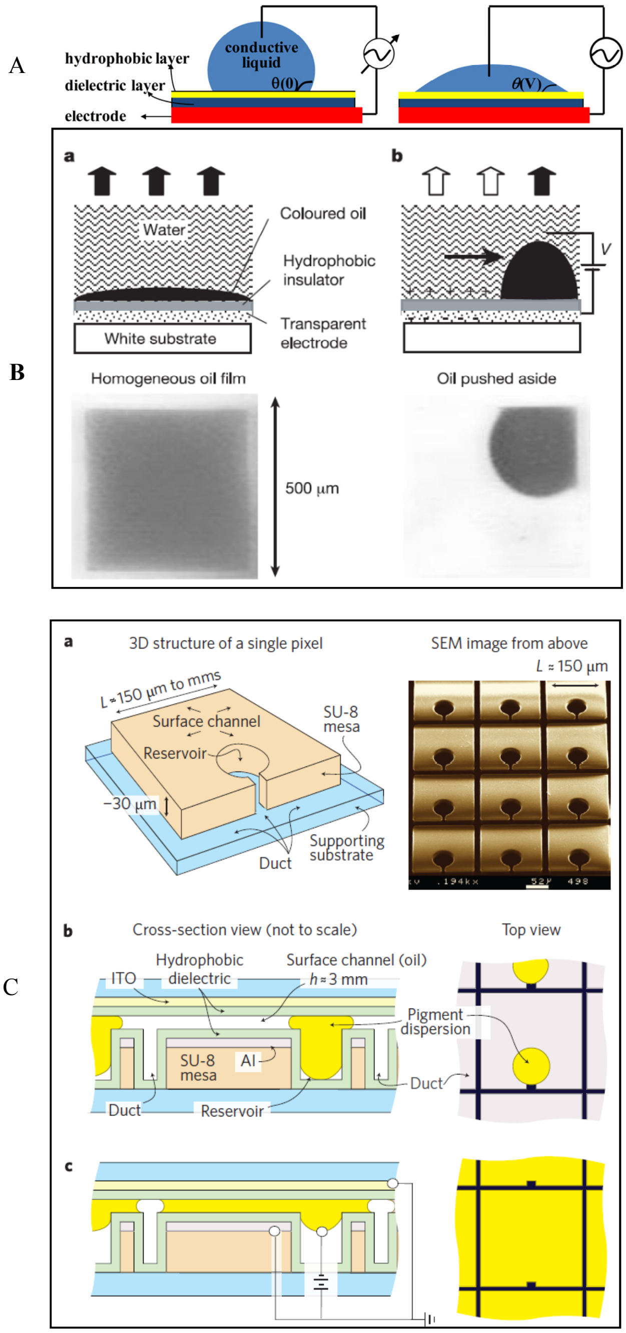

Fig. 6. (A) Schematic of electrowetting working mechanism. (B) Basic pixel of electrowetting display. (a) No voltage applied, therefore a colored homogeneous oil film is present; (b) voltage applied, causing the oil film to contract. Top row, diagrams; bottom row, photographs. The photographs show typical oil motion obtained with a homogeneous pixel electrode (Reprinted from ref.[63] with permission from Nature Publishing Group). (C) The three-dimensional pixel structure and basic pixel operation of electrowetting-based electrofluidic display. (a) Three-dimensional diagram of a single pixel (left) and scanning electron microscope (SEM) images (right) of the SU-8 mesa structure. (b) and (c) Cross-sections (left) and top views (right) of the pixels with no voltage (b) and an applied voltage (c) sufficient to cause the pigment dispersion to fill the surface channel. The microfluidic display pixel includes the top layer which is glass coated with 50-nm thin In_2O_3:SnO_2 film as transparent electrodes and

fluoropolymer layer as dielectric hydrophobic layer. The bottom plate is micro patterned by SU-8. The surface channel area is deposited an aluminum layer as electrode and reflective material, and fluoropolymer layer as hydrophobic dielectric surface of the channel (Reprinted from ref.[64] with permission from Nature Publishing Group).

Young's equation and a simplified electrowetting equation can be provided as:[66, 67]

$$\cos\theta_v = \cos\theta_0 + \frac{\varepsilon V^2}{2\sigma\lambda} \quad (4)$$

In this equation, θ_v is the contact angle between the liquid and the hydrophobic surface at applied voltage V, θ_0 is the static contact angle without applied voltage, ε is the dielectric constant of the insulator material, σ is the interfacial tension between two fluids, and λ is the thickness of the insulator. As seen from equation (3), to obtain the same value of contact angle the applied voltage is determined by the properties of materials (dielectric constant and fluidic interfacial tension) and the thickness of the dielectric material. The switching speed of EWD can easily reach 20 ms, which is currently the most attractive technology for video-speed electronic paper display.[5]

Extensive work has been done to improve the display stability, lifetime, brightness, contrast and color gamut since Hayes published his paper in Nature.[63, 64, 68-75] Currently, electrowetting display technology points to full-color and high-speed as its distinguishing feature. If low-cost and reliable manufacturing is achieved, electrowetting display might be the most potential technology to hit the market of color and video reflective electronic paper displays.

Liquavista and Gamma Dynamics were founded by Hayes with Feenstra and Heikenfeld in 2006 and 2009 after they published their articles in Nature and Nature Photonics, respectively. Both companies aim to develop color and video-speed electronic paper displays. Gamma Dynamics targeted e-reader specifications of 60-70% brightness (white state), >10:1 contrast ratio, 8-16 digital states grayscale, 1024 color, >40% color saturation, <30 ms switching speed, 15V working voltage on the active-matrix backplane. Liquavista has demonstrated their EWD products in SID. Liquavista has recently been bought by Samsung in 2011, and then sold to Amazon in 2013, which is a very strong hint that new Kindle technology based on EWD might be brought to e-reader market soon by this largest e-book company in the world.

2.4 Magnetic Fluidic Display (MFD)

Magnetic fluid is a colloidal dispersion made of magnetic particles suspended in a carrier fluid. Similar to electrically driven fluidic flow, magnetic fluid can be driven by a magnetic field. Magnetic fluid has been implemented to an optical device to modulate light intensity, and selecting different wavelength bands.[76-78] The magnetic fluid in the form of a thin film can be used to control the light transmission through the fluid by modulating its thickness [79] or selectively orientating particles.[78]

Magnetic fluidic displays have been used for magnetic drawing boards for many years.[80, 81] Magnetic fluid dispersion is sealed between plates, preferably in a pixel structure. A magnetic pen can be applied to the front of the magnetic drawing board to create an image. A magnetic strip is used to slide behind the magnetic drawing board to erase the image. This has been mass-produced for children's drawing boards. However this simply writing and erasing display technology cannot save the drawing information and display stored information, and is limited by the eraser size which a person can handle. As for a more interactive display, microfluidic based light modulator can be implemented using magnetic fluid and a controllable method.

A theoretic magnetic force can be calculated using the following equation:

$$\vec{F}_{mag} = (M_s V_{mag} \cdot \nabla)\vec{B}, \quad (5)$$

where M_s is the saturation magnetization of particles, V_{mag} is the particle volume, B is the magnetic induction which is typically described by equation 6 when it is generated by a steady current I:

$$B = \frac{\mu_0 I}{4\pi}\int_{wire}\frac{dl \times \hat{r}}{r^2}, \quad (6)$$

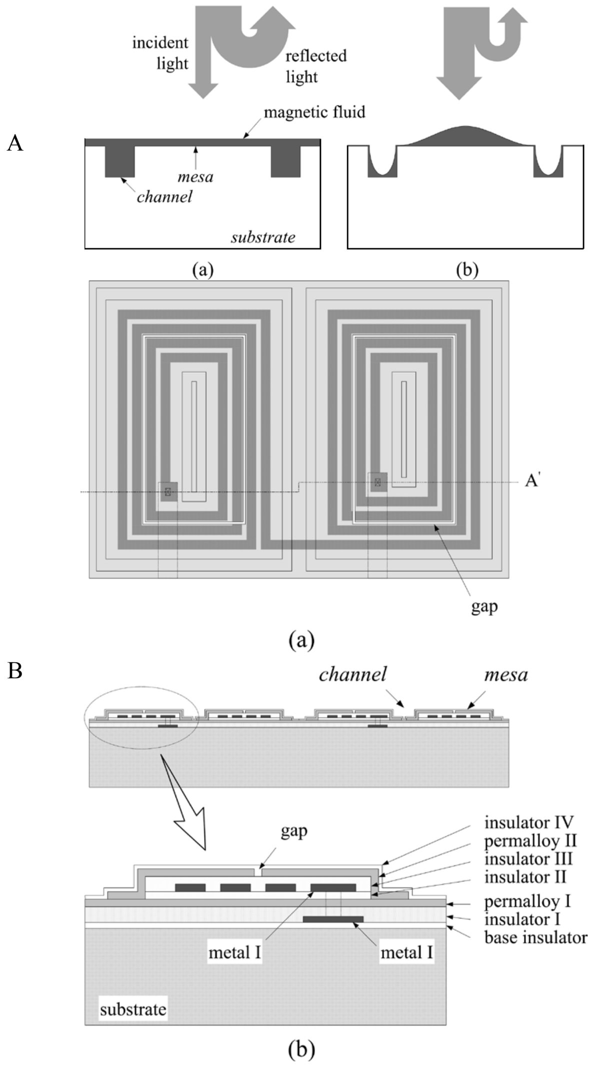

Fig. 7. (A) Schematic representation of the principle of MFD device operation: (a) light state with a thin magnetic fluid on the pixel surface reflecting much of the incoming light, and (b) dark state with a thick magnetic fluid on the cell surface absorbing much of the incoming light. (B) Schematic representation of device structure: (a) top view, showing the spiral electrode coils and the rectangular magnetic gaps, and (b) cross-sectional view of the device with a magnified view, showing the vertical layer structure of the device (Reprinted from ref.[79] with permission from IEEE).

where μ_0 is the magnetic constant, the integral sums over the wire length where vector dl is the vector line element with direction in the same sense as the current I, r is the distance between the location of dl and the location at which the magnetic field is being calculated, and $\hat{r}$ is a unit vector in the direction of r. The typical magnetic force of 0.01~500 pN have been obtained with magnetic particles diameter of 4~4500 nm under the magnetic field gradient of ~10^3 T/m.[82]

A magnetic microfluidic flat panel display device has been fabricated using MEMS technology and driven by electrical field.[83] The operation is that, the magnetic field produced by the current exerts a magnetic force on the magnetic fluid and drives it to cover the pixel surface, showing magnetic fluid color; and the surface tension of the fluid provides a resorting force when the field is reduced, showing substrate color. The optical reflectance of the pixel (brightness) is determined by the liquid thickness which was modulated by the magnetic field generated by the current. Fig. 7 shows the display operation mechanism and the structure of the display cells. In this device, the actuation of the fluid can be completed in ~12 ms for both thin-to-thick and thick-to-thin fluid film switching by magnetic forces and surface tension forces, respectively. The driving current is $\leqslant$100 mA, and the switching speed is not dependent of the driving current.

The practical problems such as particle sticking, particle confinement and other non-idealities limit the real applications of magnetic fluids in different fields. A lot of research has been done to improve the magnetic fluid properties for display applications:[77, 79, 84, 85] creating magnetic particles with low polydispersity to improve display clearance, coating particles with sol-gel materials to minimize the tendency of the magnetic particle aggregation, to enhance particle mobility, and to improve image stability; tuning the liquid viscosity by adding thickener, and applying surfactants to change the interfacial tension and stabilize particles in liquid.

The MFD technology for writing board has been developed for many years, and its products are widely used as preschool and kindergarten educational toys by taking advantages of erasability and scalability. Since it is cheap and easy to make, there are a lot of companies making products of it. However, the electronically driven MFD is still difficult to make, limited by current materials and technology.

2.5 Cell Actuation Display (CAD)

In our lives, there are a lot of natural examples of color displays demonstrated by animals. The ability to control the concentration of different pigments in chameleons' skin cells gives chameleons their color changing ability.[86-88] The color change of animals is manipulated by chromatophores, containing red, yellow, blue, and brown pigment granules lying in distinct layers just underneath the scaly surface. Chromatophores can rapidly relocate their pigment granules, thereby influencing the animal's color. Dispersion of the pigment granules in the chromatophores sets the intensity of each color.

The way squids can change their pattern of pigmentation with respect to the substrates is particularly striking. A squid tends to contract its pigment-containing cells so that the pigment becomes concentrated in tiny, widely spaced flecks; the body as a whole thus becomes lighter. On a dark background, the pigment cells expand, diffusing the pigment over a larger area and making the body darker.[88, 89] Fig. 8 shows the mechanism of cuttlefish color change. The chromatophores in the skins of these animals consist in flexible bags containing a colored liquid – red, blue, yellow, black or white. Each bag has a ring of threadlike contractile elements which can pull the bag out into a flat disk showing the fluid color, or let it collapse into a tiny sphere showing the next

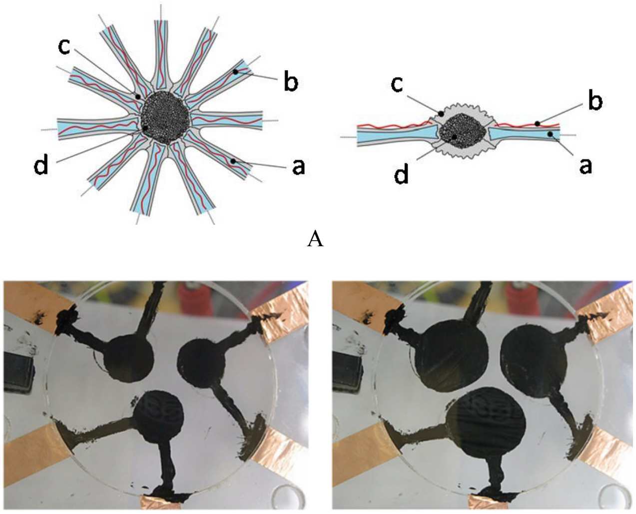

Fig. 8. (A) Diagram of horizontal (left) and vertical (right) sections through a retracted chromatophore organ of the squid, *Loligo opalescens*. Expansion of the chromatophore occurs as follows: motor signals innervate radial muscle fibres (a) to retract via nerve terminals (b), which unfolds the cell membrane (c) and biaxially stretches out the elastic sacculus (d), which contains pigment granules. (Reprinted from ref.[89] with copyright from IOP) (B) Examples of triple disc artificial chromatophores network showing "off" (left) and "on" (right) states. (Reprinted from ref.[90] with copyright from AAAS)

layer color. Therefore, learnt from the smart animals and with the help of smart materials, scientists recently have mimicked the color change of cuttlefish by electrically shrinking or expanding the "cell" to display color.[89, 90] However, the "cell" materials, the pigments, the way of relocating pigments in "cells" and the signal process all are still at early stage.

3. Conclusion

For information displays, the method which can emit light or control light intensity in the visible wavelength could be applied. Microfluidics, which can manipulate fluids at the microscale are highly suitable for display applications since fluids can modulate light, and function as display pixels when they are confined in microscale arrays. At the microscale, taking advantages of both microfluidics and microtechnology, and combining with large surface area and dominant surface tension, people have managed to create several microfluidic-based displays including PPD, EFD, EOD, EWD, MFD, and CAD. In these technologies, EPD have been successfully commercialized for e-Reader market, MFD has been widely produced for children's writing boards, and EWD is also developing quickly to hit video-speed reflective color display market. Others like EOD, PDD and CAD would also revolve quickly and widely when materials and technologies are matured enough. It is still difficult to compare all these technologies in this early stage since some of them have just being involved in this area. Table 1 summarizes the optical performance and current status of technology for paper, LCD, EPD, EFD and MFD.

The main requirements for display applications are: pixel level controllability including reversibility, speed, brightness, power consumption and flexibility. In order to satisfy those requirements, microfluidics with optics, electronics, interfacial chemistry and physics, is forming a multidisciplinary research community. When the corresponding large community of interest

Table 1. Optical performance and technology status of paper, LCD and some microfluidic-based electronic paper-like displays.[5, 21, 61, 64, 74, 83, 91-95]

	Paper	LCD	EPD	EFD	MFD
Reflectivity	>60%	Trans missive	45%	60%	~40%
Contrast ratio	~10:1	Trans missive	10:1	15:1	10:1
Color	+	++	-	+	-
Speed	0	2 ms	150 ms	7.5 ms	12 ms
View angle	++	-	+	+	+
Driving	0	5 V	15 V	15-20 V	100 mA
Flexible	++	-	+	+	-
Product	Book/ News-paper/ Magazine	TV/ Labtop/ Mobile phone/ PC screen/ Camera	e-Reader/ Digital signage/ Smart watch	PC screen (prototype)/ Digital watch (prototype)	Drawing board/ Tactile screen
Company	Many	Many	E-ink/ HP/ Philips/ IBM/ Canon/ OED	Amazon/ Gamma Dynamics/ ADL/ Etulipa	Many

* The data in this table is based on the cited references and information from the website of those companies.

builds around this technology, it would drive the technology to irresistible development and maturity. In the future, electronic-ink would be expecting to be printed in/on any surfaces and actuated by many means of technology. The ink itself is fluidic, which would make it possible to develop flexible paper-like displays. By taking the advantages of microfluidics, some microfluidic technologies like electrowetting are being expected to realize video-speed electronic paper-like displays.

Electronic paper-like displays have the advantage of use in both indoor and outdoor environments, the possibility of bi-stable and low power consumption (especially at low speed like e-books, digital signage and equipment screens), and easy readability due to their principle of reflective display. In summary, the desire for electronic paper-like displays is very strong. It is estimated by the Price Water House Coopers that the E-paper market will be about 8.2 billon US dollars, more than paper in the book market. The challenge for Electronic paper-like displays is to develop suitable frontplane technology including materials and processing, and the backplane like active matrix with fully functioning electronic hardware and optimized waveform.

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5. Notes

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