Video-speed electronic paper based on electrowetting

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In recent years, a number of different technologies have been proposed for use in reflective displays1-7. One of the most appealing applications of a reflective display is electronic paper, which combines the desirable viewing characteristics of conventional printed paper with the ability to manipulate the displayed information electronically. Electronic paper based on the electrophoretic motion of particles inside small capsules has been demonstrated8 and commercialized; but the response speed of such a system is rather slow, limited by the velocity of the particles. Recently, we have demonstrated that electrowetting is an attractive technology for the rapid manipulation of liquids on a micrometre scale9. Here we show that electrowetting can also be used to form the basis of a reflective display that is significantly faster than electrophoretic displays, so that video content can be displayed. Our display principle utilizes the voltage-controlled movement of a coloured oil film adjacent to a white substrate.

The reflectivity and contrast of our system approach those of paper. In addition, we demonstrate a colour concept, which is intrinsically four times brighter than reflective liquid-crystal displays10-12 and twice as bright as other emerging technologies1-3. The principle of microfluidic motion at low voltages is applicable in a wide range of electro-optic devices.

Microfluidic movement based on electrowetting4,6,7—where a voltage difference between a hydrophobic solid and a liquid causes a change in wettability—is being used for an increasing number of applications. These include pixelated optical filters4, adaptive lenses5 and lab-on-a-chip13. Electrowetting has several very attractive features for use in micrometre- to millimetre-sized systems: low power consumption, fast response speed and scalability. In addition, when a fluoropolymer coating with low contact-angle hysteresis is used, a high degree of reversibility can be obtained14. However, in most of the applications reported a thick insulator is used, giving rise to high switching voltages. By improving the processing of hydrophobic insulating materials we managed to lower the drive voltages dramatically15-17, opening up a much broader application area.

For the electrowetting display principle, the focus is on the movement of a confined water–oil interface (Fig. 1). In equilibrium, a coloured oil film lies naturally between the water and the hydrophobic insulator coating of an electrode, because

$$\gamma_{0,w} + \gamma_{0,i} < \gamma_{0,i}$$

(1)

where \(\gamma\) is the interfacial tension, and the subscripts denote the oil, water and insulator, respectively. Owing to the dominance of interfacial over gravitational forces in small systems (<2 mm), such an oil film is continuous and stable in all orientations. However, when a voltage \(V\) is applied between the substrate electrode and the water, an electrostatic term \(-\varepsilon CV^2/2\) is added to the energy balance, and the stacked state is no longer energetically favourable (Fig. 1b). The system can lower its energy by moving the water into contact with the insulator, thereby displacing the oil.

The balance between electrical and capillary forces determines how far the oil is moved to the side. Hence the optical properties of the stack, when viewed from above, can be continuously and reversibly tuned between a coloured off-state and a transparent on-state, assuming that the pixel is sufficiently small that a viewer

![Figure 1](image)

**Figure 1** Electrowetting display principle. a. No voltage applied, therefore a coloured homogeneous oil film is present. b. d.c. voltage applied, causing the oil film to contract. Top row, diagrams; bottom row, photographs. The photographs show typical oil motion obtained with an homogeneous pixel electrode.
experiences the average optical response. Alternatively, if a diffusely
reflective (white) surface is placed under the switchable element, a
simple high-brightness/high-contrast optical switch is obtained
that can be used as the basis for a reflective display. It has been
previously proposed\(^1\) that electrowetting could be used as a display
principle by driving a refractive index matched liquid into a three-
dimensional porous network to provide the optical modulation
from white to transparent. Optical performance aside, applying the
metallic and insulating layers required for reversible electrowetting
in such a porous network renders this principle highly impractical.
In contrast, the microfluidic motion demonstrated here is two-
dimensional, which can be practically realized using the currently
available (and reliable) electrowetting device materials over large
display areas.

In our system, the white reflector is integrated into the optical
stack by coating a white polymer foil with a thin, patterned (15 nm
indium tin oxide, ITO) electrode layer and a fluoropolymer insu-
lator. The moving oil film is now separated from the white substrate
by just the thickness of the electrode/insulator combination (typi-
cally <1 \(\mu m\), resulting in a very efficient recycling of ambient light.
Oils of any required colour are formulated by dissolving non-polar
dyes in alkanes (typically \(C_{10}\)–\(C_{16}\)). As a large variety of oils and
polar liquids can be used, we can adapt our system to the tempera-
ture requirements. To contain the oil films on a pixel resolution, we
use a thin film fabrication procedure. A black or transparent
polymer sheet, typically 50 \(\mu m\) thick, is laser cut to provide the
required pixel sizes and patterns. It is then glued onto the insulator-
covered substrate with a low viscosity two-part epoxy. Liquids
are dosed and the test cells are sealed with an ITO-covered glass
slide.

The electro-optic characteristics of a single electrowetting pixel
measured at 0° with diffuse illumination are shown in Fig. 2. A small
threshold voltage is observed before displacement of the oil film
commences. Very little hysteresis in fluid motion is observed. The
intermediate optical states are stable, implying that analogue,
voltage-controlled grey scales can be realized. At a voltage of about
−20 V, the oil film has contracted dramatically and in excess of 70% of
the white substrate is exposed, resulting in a reflectivity of about
35% (left-hand axis in Fig. 2). At higher voltages, where the electro-
optic curve plateaus, up to 90% of the white substrate becomes
exposed. The contraction of the oil results in a maximum contrast of
about 15. We determined the contrast (the reflectivity ratio with
and without voltage) and the reflectivity at the centre of the absorption
band (550 nm), because we used a coloured dye that absorbs only
part of the visible spectrum. The full wavelength response (Fig. 2
inset) is indicated for 0 and −20 V. The reflectivity \(R\) and contrast
obtained are comparable to the optical properties of electrophoretic
displays (\(R\approx 40\%\) and contrast \(\approx 11\))\(^3\), and are approaching
the optical performance of paper (\(R\approx 60\%\) and contrast \(\approx 15\)).

The main pixel parameters that influence the electro-optical
performance are the thickness of the oil film and the thickness of
the fluoropolymer insulator. As the oil film becomes thicker, the
electro-optic curve is shifted to higher field strength. As a result, it is
best to work with an oil film thickness that is sufficiently thin to give
low operating voltage, while sufficiently thick to ensure a satisfac-
tory optical activity (typically around \(10 \mu m\), that is, nanolitre
volumes of oil). The thickness of the insulator determines the
necessary field strength as soon as the oil has moved (partly)
aside. Hence the insulator should be as thin as possible, while still
having sufficient dielectric strength\(^4\).

In small pixels, the motion of the oil film is sufficiently fast to
show video content (Supplementary Information). The optically
measured response speed in a 250 \(\times\) 250 \(\mu m^2\) pixel (equivalent to
100 pixels per inch) is shown in Fig. 3. Both the on-switch and the
off-switch show a response time close to 10 ms. The on-switch is
voltage driven, while the off-switch relies solely on capillary forces
to reform the oil film. We have recently commenced the evaluation
of larger arrays of electrowetting pixels, and introduced individual
pixel addressing (Supplementary Information). Sealed pixel arrays
exhibit no deterioration in electro-optic performance after several
million switches. The individual pixel addressing in larger-size
displays can be provided by active matrix technology.

One of the major drawbacks of current reflective display tech-
nologies is their low colour-reflectivity, mostly because of the use of
RGB (red-green-blue) colour segmentation\(^1\)–\(^3\). In Fig. 4a we show a

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**Figure 2** Electro-optic behaviour of electrowetting display pixels. Reflectivity and contrast as a function of d.c. voltage for a 500 \(\times\) 500 \(\mu m^2\) pixel with a 15-\(\mu m\)-thick magenta oil layer and a 0.8-\(\mu m\)-thick fluoropolymer insulator. Inset, full wavelength response.

**Figure 3** Electrowetting pixel kinetics. Temporal behaviour of a 250 \(\times\) 250 \(\mu m^2\) pixel, demonstrating the video-speed response. The oil film thickness is 15 \(\mu m\) and the insulator thickness is 0.8 \(\mu m\). The on and off response times are 12 and 13 ms respectively. The reflectivity is shown in normalized units, which does not affect the time
axis. \(t_{on}\) and \(t_{off}\) are defined as the time it takes to complete 90% of the optical
modulation. Insets, photographs showing the corresponding optical state for a 3 \(\times\) 3
array of 500 \(\times\) 500 \(\mu m^2\) pixels. With a homogeneous pixel electrode, the observed oil
motion is reproducible for a given pixel but is variable between pixels. Motion to a specific
position in a pixel array can be realized by using an inhomogeneous pixel electrode
(Supplementary Information).
colour concept for an electrowetting display that has a reflectivity that is four times higher than that of a reflective liquid-crystal display (LCD) and twice as high as other emerging technologies. In this case, a single display pixel would comprise three subpixels. In each of the subpixels a second oil layer is added, orthogonally oriented with respect to the upper plate. With a hydrophilic pixel wall, the sandwich structure with two oil layers is the stable equilibrium state. Each oil layer can be switched independently and reversibly by applying a voltage difference between the water and the top or bottom plate. In this case, a single display pixel would comprise three subpixels. In each of the subpixels a second oil layer is added, orthogonally oriented with respect to the top plate. With a hydrophilic pixel wall, the sandwich structure with two oil layers is the stable equilibrium state. Each oil layer can be switched independently and reversibly by applying a voltage difference between the water and the top or bottom plate.

A combustion-free methodology for synthesizing zeolites and zeolite-like materials

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Zeolites are mainly used for the adsorption and separation of ions and small molecules, and as heterogeneous catalysts. More recently, these materials are receiving attention in other applications, such as medical diagnosis and as components in electronic devices. Modern synthetic methodologies for preparing zeolites and zeolite-like materials typically involve the use of organic molecules that direct the assembly pathway and ultimately fill the pore space. Removal of these enclathrated organic structure-directing agents (SDAs) that can be disassembled within the zeolite pore space to allow removal of their fragments for possible use again by reassembly. The methodology is shown for the synthesis of zeolite ZSM-5 using a SDA that...

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