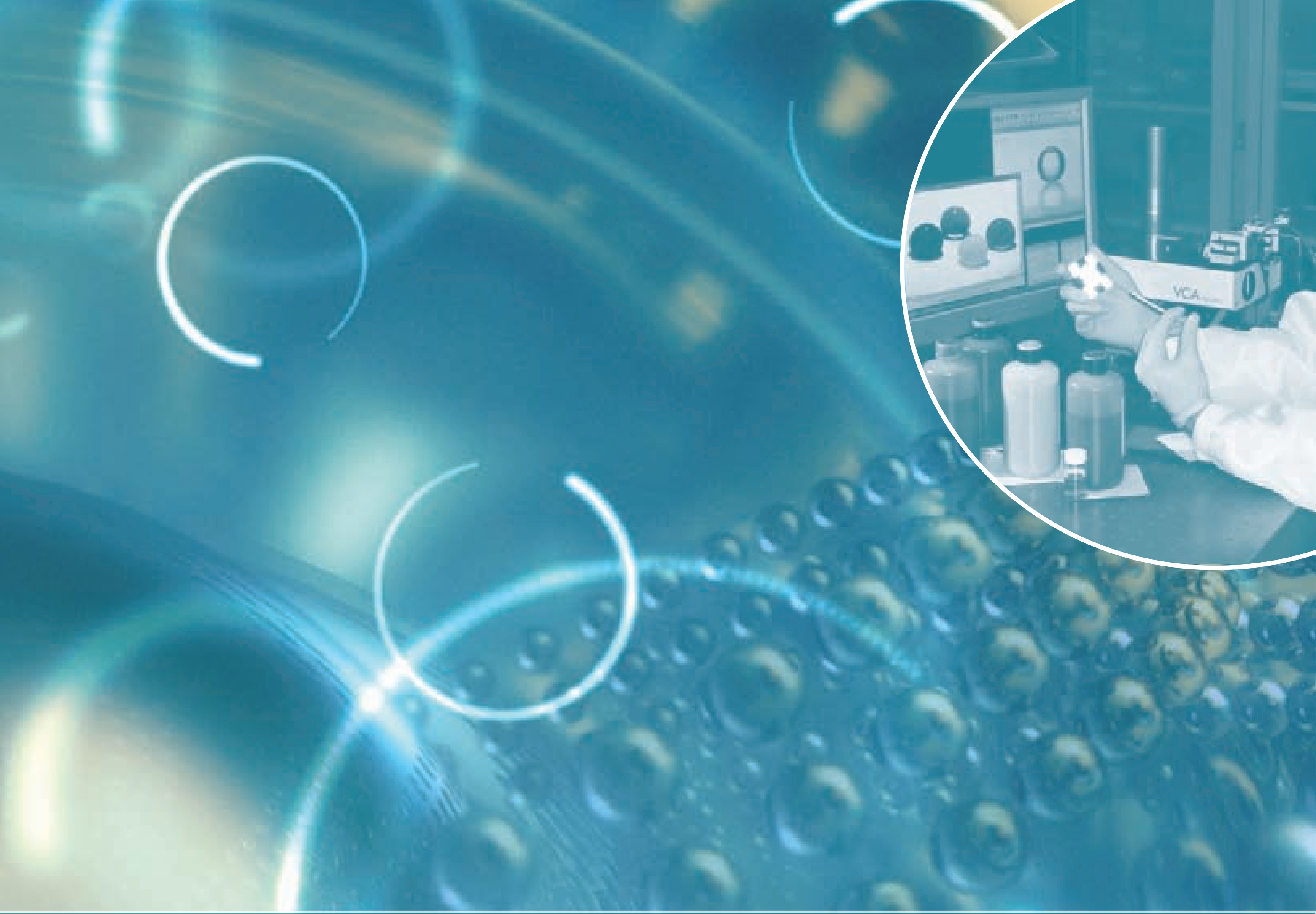

Recent Progress in Arrayed Electrowetting Optics

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Electrowetting devices can now be formed in arrays covering thousands of square centimeters of glass. New research is pointing the way toward exciting applications for laser radar, 3D displays, adaptive camouflage, electronic paper, retroreflector communication and lab-on-a-chip.

Electrowetting—a technique for manipulating small amounts of liquid on surfaces—has considerable roots in optics. Nearly a century after Lippmann's groundbreaking work in electrocapillarity, Beni and Hackwood first coined the term electrowetting in their 1981 publication *Electrowetting Displays*. A decade later, Berge's 1993 report on the reversible electrowetting of dielectrics unleashed real excitement and potential for electrowetting. Berge quickly transformed this fundamental breakthrough into a switchable lens device, founded the company Varioptic, and released the first commercial product for electrowetting in 2006—the Artic 320 Liquid Lens.

Another watershed event was the 2003 *Nature* article by Hayes and Feenstra (Philips) on colored-oil electrowetting displays. At the same time, there was an explosion of interest among physicists and engineers in fundamental electrowetting science and applied electrowetting for lab-on-a-chip applications. These breakthroughs have led to a gold rush in electrowetting research, as documented by a 70 percent annual increase in patents and publications related to this area.

Despite this explosive growth, academia and industry have been slow to investigate additional forms of electrowetting optics. This is surprising, given the maturity of the commercial photonics market and the clear need for next-generation photonic technologies. At best, we can only speculate on the root cause of this disconnect. In some cases, electrowetting optics may seem foreign to researchers who are more accustomed to working in traditional solid-state photonics. Furthermore, electrowetting optics pose a greater fabrication challenge than optofluidic devices, which often rely on bulky peripherals such as syringe pumps. Arrayed electrowetting optics are more self-contained and require materials that must satisfy electrical, optical, fluidic and chemical requirements.

However, research in electrowetting optics might now be poised for a major upsurge. For example, in the past two years at Cincinnati, we have expanded the field to include several novel high-performance platforms in arrayed electrowetting optics. New technologies include electrowetting microprisms with beam steering that previously could only be achieved by tilting a bulk optic. Also, electrowetting with colored liquids can now provide reflective pixels that are on par with the brilliance of pigments printed on paper. New electrowetting technologies have the potential to break through many longstanding barriers in laser radar, 3D displays, adaptive camouflage, electronic paper, retroreflector communication and microlens arrays. We might be witnessing the beginning of a revolution in electrowetting optical research, supported by continued industrial successes and new efforts emerging in Germany, Israel, Japan, Taiwan and other countries.

Inset photo: The author, Jason Heikenfeld, holding an electrowetting retroreflector prototype. Testing of electrowetting liquids is visible in the background.

Getty Images/Inset courtesy of J. Heikenfeld

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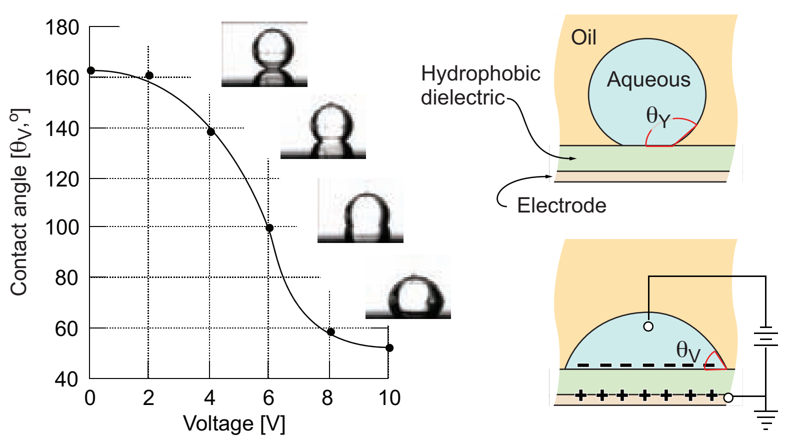
Basic features of arrayed electrowetting optics

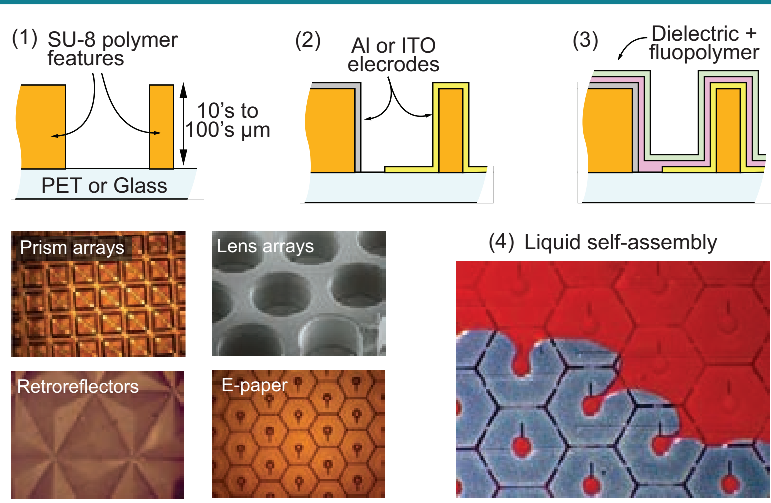
Berge's modern electrowetting system consists of an aqueous solution that is electrically insulated from a planar electrode by a hydrophobic dielectric. In equilibrium, the aqueous solution exhibits a large Young's contact angle (θ_Y), ranging from about 160° to 180° in an oil environment. When voltage (V) is applied, the contact angle projection can be reduced by more than 100° to the electrowetted contact angle (θ_V). As Jones described in 2005, an electromechanical force physically governs this electrowetting effect. Contact angle vs. voltage is predicted by the so-called electrowetting equation: $\cos\theta_V = \cos\theta_Y + CV^2/2\gamma$, where C is capacitance per unit area of the hydrophobic dielectric and γ is the interfacial surface tension between the aqueous liquid and the oil.

At Cincinnati, we often use high capacitance Al_2O_3 / fluoropolymer dielectrics that permit operation at less than 10 V. The advantage of low voltage is not power consumption—since electrowetting requires a mere 0.1 to 1 μJ/cm^2 per switch—but rather that such voltage allows each element or small group of elements to be controlled by a thin-film-transistor. This "active-matrix" control with arrayed thin-film transistors provides: (1) accurate control over the entire substrate, even with fabrication non-uniformity; (2) compatibility with an industrial infrastructure that produces liquid-crystal displays with diagonals greater than 100 in.; and (3) high speed and independent control of each electrowetting element.

[Electrowetting basics]



[3D fabrication of arrayed devices]



With switching speed, the limiting factor is the response time of the electrowetting element itself. At the device scales pursued at Cincinnati—around tens of micrometers—a contact line velocity of about 10 cm/s is predictive of switching speed. For example, a device that requires the three-phase water/oil/fluoropolymer contact line to move about 10 μm can be switched at roughly 10 kHz. At such small scales, damping of meniscus oscillation, gravity and vibration all have little influence on device operation. The switching speeds for electrowetting optics are inadequate for high-speed data transfer, but are comparable to the speeds required for numerous applications that currently use micro-electro-mechanical or liquid-crystal devices.

Electrowetting optical devices are always highly non-planar in geometry (i.e., unlike electro-optic polymer or liquid-crystal devices). Every device requires separate volumes of oil and water and a substantial geometrical change between the oil/water meniscus. Furthermore, for most electrowetting optical devices, the solid materials are also 3D in geometry. To create such structures, we have leveraged the photo-epoxy processing for thick films (1s to 100s of μm) that is extensively used by the microfluidics community. However, for electrowetting optics, we face additional challenges because we must conformally coat this 3D scaffold with electrodes, dielectrics and photoresists. Moreover, because the 3D scaffold is a polymer, processing temperatures must generally be kept less than 180° C. Cincinnati's fabrication process is therefore less like traditional silicon microfabrication and more akin to the emerging fields of flexible and organic electronics. In fact, we currently only use photolithography, deposition and wet-etching to fabricate all the devices that we will review here.

One notable feature of our fabrication process is how we perform discrete dosing of liquids into microscopic features. We do not use serial dosing techniques such as ink-jet. Instead, we have created several novel techniques for liquid self-assembly. Self-assembly provides parallel dosing of non-polar liquids (oil), polar liquids (water), and co-solvents with precise control of liquid volume inside any device cavity. With self-assembly, our fabrication area can defensibly be tens of thousands of square centimeters and consist of millions of individual electrowetting elements of 10s to 100s of micrometers each.

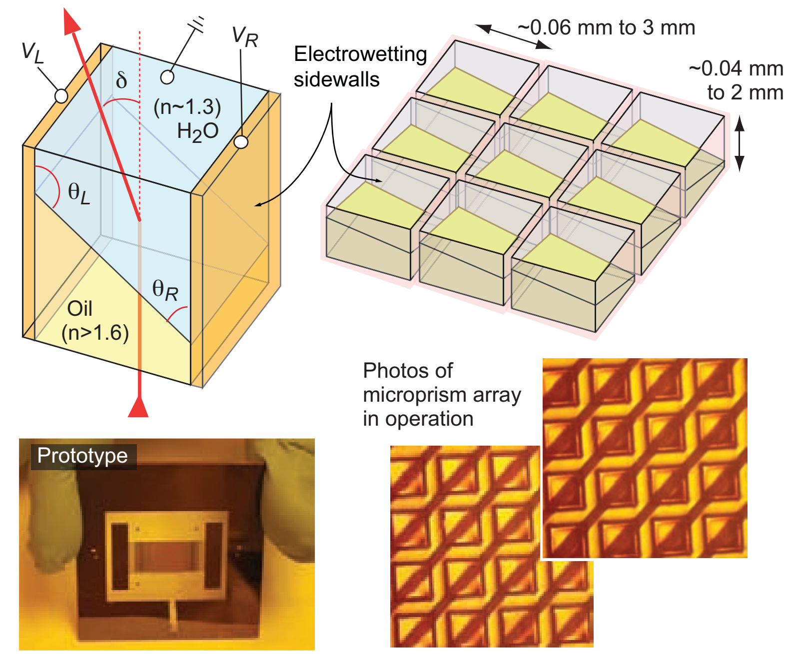
Arrayed elecrowetting prisms and lenses

Beam steering technology has been a limiting factor for laser radar, agile imaging, 3D displays and numerous other applications. This is because current approaches cannot yet provide large-area, thin, transmissive and wide-angle beam deflection. Researchers continue to make substantial progress in the area of liquid crystal beam steering. For example, Kent State scientists are developing a new vertically aligned phased-array, and N.C. State has reported a new wide-angle approach using polarization gratings. Regarding micro-electro-mechanical (MEMs) technology, several solutions are well-developed for beam steering but are reflective only—which causes a large system footprint. What is still lacking is a continuous beam steering architecture that is thin, wide angle (>+/–30°), and can efficiently transmit light of multiple wavelengths and polarizations.

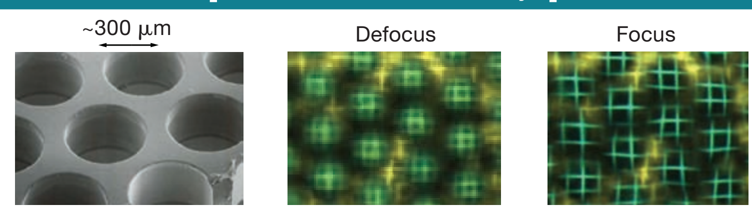
Although not switchable, prismatic plates like those long used in lighthouse Fresnel lenses provide most of the desired features for a wide-angle beam-steering element. One might therefore argue that the ultimate platform would use highly refractive material and simply alter its geometry.

Electrowetting microprisms operate by modifying the physical geometry between two immiscible liquids. In an electrowetting microprism, low index water (n~1.3) and high index oil (n>1.6) are confined by at least two electrowetting sidewalls.

[Arrayed elecrowetting microprisms]



[Switchable microlens arrays]



These sidewalls are connected to two distinct voltages (V_L, V_R) that independently control the water contact angle at each sidewall (θ_L, θ_R). As long as the voltages are selected such that $\theta_L+\theta_R$=180°, the meniscus is held flat and a variable prism is created.

Arrayed electrowetting prisms and lenses

Demonstrated: The arrayed format was demonstrated at the University of Cincinnati in 2007. The single electrowetting lens was developed by Berge (Varioptic) in the late 1990s.

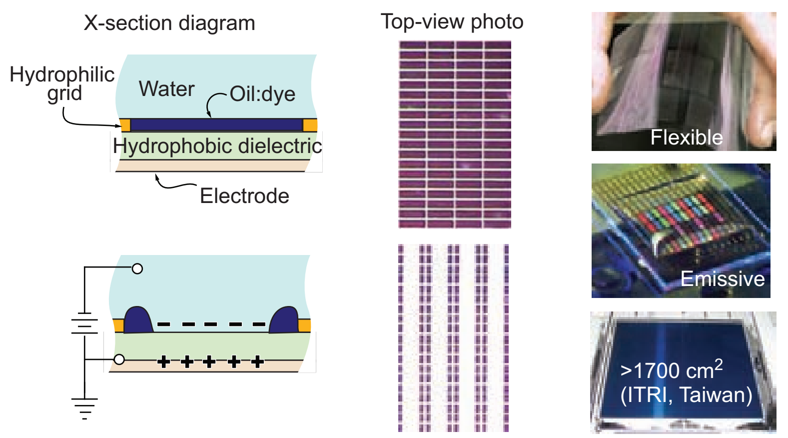
How it works: Each element controls 2D curvature of the meniscus between high index oil and low index water.

Key advantages: Wide angle (>+/-30°) and low loss beam or image steering, or invertible concave/convex lens arrays.

Key challenges: Many beam steering applications require continuous phase and therefore very precise control.

We have already shown the total beam deflection to be greater than 20°, and we project that future devices will have total beam deflection in the range of 60° to 80°. At Cincinnati, we are now able to stabilize the liquids with four electrowetting sidewalls. When such microprisms are formed in large arrays, two operating modes are possible. The first is two-dimensional refractive steering. For this, all four sidewalls are biased with voltage, and beam steering is enabled over all angles within a cone. The second mode is discrete and one-dimensional phased-array steering. Here, each individual prism is a single period in a sawtooth phase profile with fixed pitch but variable amplitude.

[Planar electrowetting displays]



The phase reset at each prism must be some value of n2π in order to create what is optically similar to a continuous phase ramp (i.e., like that of a single large prism). This second approach is certainly more challenging. However, four thin-film transistors can theoretically provide the bit-level needed for λ/10 control of several adjacent microprisms. Although this second mode of steering is discrete, simple 0-2π fine steering elements are readily available. The fine-steering element would be placed before the microprism array and thus permit continuous beam steering over a large arc.

Compared to other forms of electrowetting optics, electrowetting microprisms pose the greatest fabrication challenges. Electrodes must be patterned on vertical sidewalls and be coated with a hydrophobic dielectric. Currently, we can achieve electrode patterning for 300 × 300 μm^2 prisms that are arrayed on 2 × 2 in. substrates. We are focused on reducing the side-wall thickness (fill factor) and implementing high-resolution photolithography on the sidewalls. These efforts will lead us to microprisms that are 50 to 100 μm in size, with fill factors of greater than 90 percent. Electrowetting microprism arrays can arguably be thin panel and provide fast and wide-angle steering. Such capability is ideal for applications such as laser radar or 3D displays.

Using a simplified version of the fabrication techniques used to make microprism arrays, we have recently demonstrated switchable microlens arrays. They are controlled by a single electrode and can be inverted from convex to concave, much like a Varioptic or Philips liquid lens. However, in arrayed format, such lenses have myriad applications, including stereoscopic displays, adaptive optic technologies, laser array collimators and portable wave-front sensors. Recently, there has been a major increase in reports of switchable microlens arrays based on liquid crystal and other technologies. Electrowetting microlens arrays can invert focal length; can achieve nearly hemispherical lens curvature; and are simple to fabricate. Therefore, they may present some advantages over competing approaches.

Electrowetting displays

Demonstrated: Oil-dye was demonstrated in 2003 at Philips Research Labs; water-pigment displays were shown in 2007 at the University of Cincinnati.

How it works: Electrowetting is used to tranpose the positions of two liquids, one of which is clear and the second of which is brilliantly colored.

Key advantages: Highest white reflectivity of any display technology (R>60 to 85%).

Key challenges: For oil-dye trade-off between pixel size, color saturation, and voltage. For water-pigment analog grayscale not yet available.

Electrowetting displays

In some ways, the flat panel display market is extremely mature. Wide-screen plasma and LCD TVs are now commonplace, and e-book technologies (e.g., the Amazon Kindle) are readily available as well. However, people who work outside displays may be surprised to learn that liquid crystal displays are typically less than 10 percent optically efficient, and the electrophoretic ink used in e-books is only about 40 percent reflective. There is therefore very good reason to pursue alternate display technologies.

Of the many new display technologies under investigation, arrayed electrowetting devices are particularly compelling. The first electrowetting display technology to capture researchers' attention was the dye-colored oil film approach discovered by Hayes and Feenstra at Philips (now at the Philips spin-off, Liquavista). This approach uses water covering a film of oil. The oil forms a film beneath the water because the water contact angle is very large (θ_Y ~160 to 180°, so the contact angle for the oil is about 20° to 0°). When voltage is applied, this water electrowets the hydrophobic dielectric, causing the oil to "de-wet" the surface. This reduces the viewable area of the oil from 100 to 20 percent. Liquavista uses a reflective material beneath the display pixel that enables an active-matrix video display with reflectivity of greater than 50 to 60 percent.

At Cincinnati, we have further developed this oil film approach. We have also investigated alternate strategies for higher brightness. Consider, for example, a backlit display like those used in laptops, TVs and cell phones. We have demonstrated the patterning of a reflector underneath the area of the oil in the electrowetted state. This approach recycles light into the backlight until the light can only exit through the optically clear portion of the pixel. As a result, more than 80 percent transmission can be achieved, resulting in higher brightness or lower power consumption.

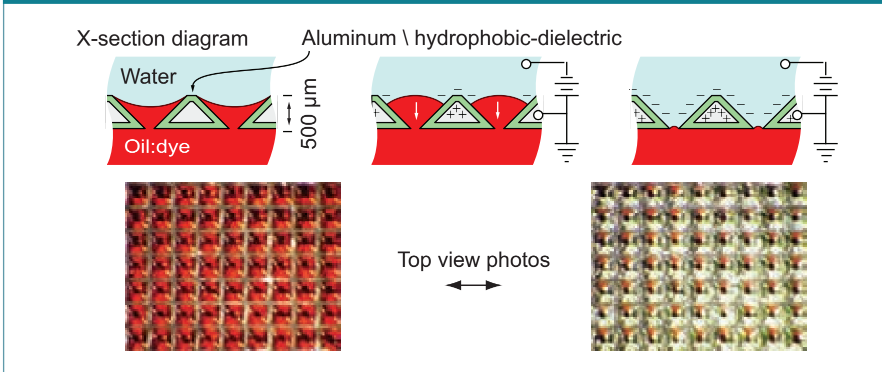
We have further created fabrication processes that can be implemented in the range of 100° to 120° C. Accordingly, we do much of our fabrication on low-cost and flexible plastic substrates (PET, PEN, etc.). In 2005, we demonstrated an emissive electrowetting display format. We created this display by doping the oil with RGB fluorescent dyes and by using the substrate as a waveguide for 400 nm pump light. At Cincinnati's electrowetting program, we work in collaboration with several companies and with the Industrial Technology Research Institute (ITRI) in Taiwan. ITRI has recently scaled the electrowetting display fabrication process to greater than 1,700 cm^2 on an active matrix backplane, using standard LCD manufacturing equipment.

Now that the traditional colored-oil film approach is well on its way to commercialization, we are focusing our research on alternate approaches for reflective displays. In 2008, we reported on arrayed electrowetting microwells, a new approach based on moving colored fluid in front of or behind a white perforated substrate. If the perforated area is small (less than 5 to 10 percent viewable), then white reflectance on the order of paper (80 to 90 percent viewable) could be achieved in displays.

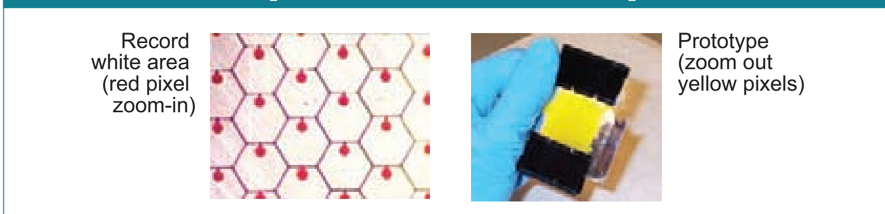
The operation works as follows: At no voltage, colored oil fills a diverging cavity such as an inverted pyramid, cone, or corner-cube. This provides brilliant coloration to a viewer at the front of the display. When voltage is applied, water electrowets the capillary; and the colored oil is largely hidden from view. This process is fully reversible and has also been demonstrated with colored water behind the substrate. With colored water, the colored/white response to voltage is simply reversed.

We have yet to publish our most recent technique for reflective displays, but it has generated excitement within our research group and collaborative circle. This new approach is temporarily named the "chromatophore" technique. We use aqueous pigment dispersions (similar to ink-jet fluid but specialized by Sun Chemical for our application). This approach appears to be more manufacturable than using the arrayed microwells. Moreover, it has the potential to be the thinnest of all electrowetting display formats (15 to 20 μm thick for all liquids). Most important, there is the potential for record white state reflectance (>85 percent).

[Electrowetting microwells]



[New project: 'chromatophore']



Another potential application for the chromatophore project is adaptive camouflage. By changing the viewable area of a pigment, these electronic chromatophores appear to be the closest mimic to a biological chromatophore. Moreover, the approach might be particularly powerful because the device can readily incorporate the specialized sensor-defeating pigments used in military camouflage. The chromatophore work related to displays has been submitted to a journal. We hope it will be published in early 2009.

Electrowetting retroreflectors

Demonstrated: This application was demonstrated in 2007 at the University of Cincinnati.

How it works: An electrowetting lenslet is self-assembled into an optical corner-cube and switches between retroreflecting and scattering.

Key advantages: Low-loss, broad spectrum (including visible) and high contrast (>10:1).

Key challenges: Attractive for numerous applications but not for high-data-rate free-space communications.

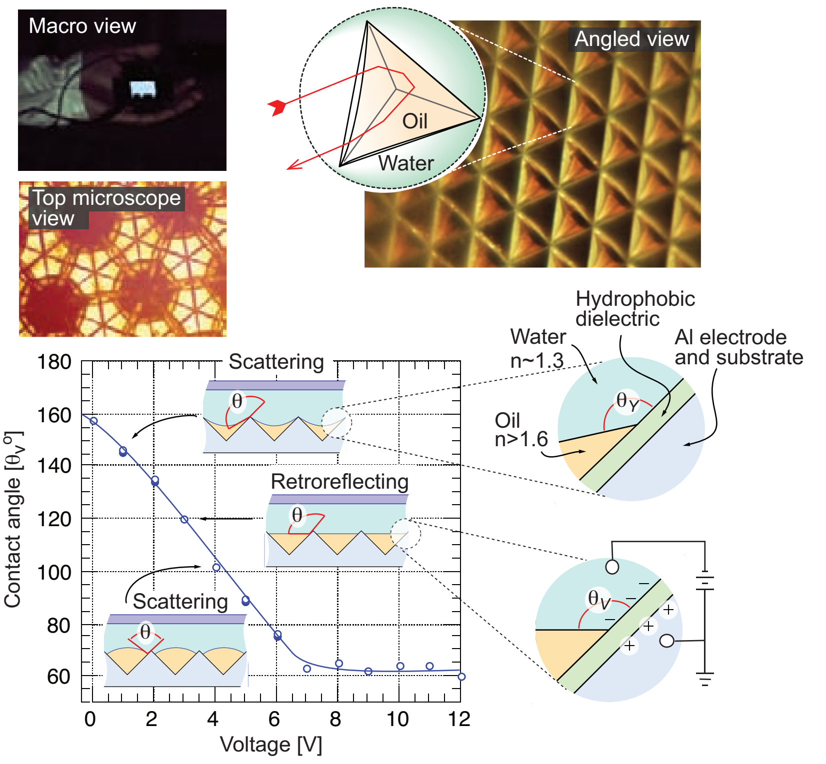
Electrowetting retroreflectors

Corner cube and spherical retroreflectors are ubiquitous in range-finding applications, since they reflect light back to the illumination source with unmatched efficiency.

Two forms of large-area retroreflectors dominate—glass beads or a truncated corner of a cube. The corner-cube approach yields several-fold higher retroreflective efficiency. A light ray incident into a corner-cube reflects off the mirrored facets and emerges parallel to the direction of incidence. As a result, an observer positioned next to the illumination source perceives a surface that is more than 50 times as bright as an optically scattering background.

Over the past decade, several forms of switchable retroreflectors have been developed. Naked-eye applications have not been strongly pursued because previous approaches are either difficult to scale to the array sizes needed for visualization at a distance, or limited to

[Electrowetting retroreflectors]



very-narrow-spectrum infrared. We have recently demonstrated an electrowetting retroreflector with the following features: low-loss and wide-spectrum, as limited only by the absorption spectrum of water; scalability to any size supported by microreplication/molding; and high contrast switching (>10:1) over a +/-30° field of view.

The operation principles for these devices are fundamentally simple. Using our liquid self-assembly processes, we form an electrowetting lenslet inside each corner cube. At no voltage, the lenslet is concave. A concave lenslet breaks the optical symmetry of the corner cube and causes it to scatter the light (semi-diffuse, large beam divergence). With as little as 3V, the water/meniscus can be electrowetted to a flat geometry and the lenslet disappears. This restores the retroreflecting nature of the corner cube, and laser light, a headlight, or a flashlight is returned to the viewer with brightness that dominates over the surrounding background.

These results could prove useful for a variety of applications, including flashing safety markings (which could have personal, road or structural uses), surveying and range finding, free-space communications, active decorative films, active barcodes, and military friend/foe ID. We are working on scaling down the microreplication to the 10-µm size range that can be achieved commercially. This is important for increasing switching speed, but also for creating the thin and flexible form factor that is already available for conspicuity tape.

Looking forward

We have reviewed arrayed electrowetting optics that deflect or focus (microprisms, lenslets), spatially modulate (pixels, microwells, chromatophores) and switchably retroreflect (corner-cubes). All of these are early stage technologies that require substantial research and development before commercialization, and the opportunity for scientific contribution is broad-reaching. Furthermore, what we have presented is merely the tip of the iceberg when it comes to inventing new forms of electrowetting optics. Fabrication processes and materials now support virtually any sort of device structure that can be arrayed, even over large optical apertures. We speculate that the most important next step for electrowetting optics is the formation of a larger global research community of optical scientists and engineers. We encourage your participation and creative thoughts for expanding this exciting field.

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