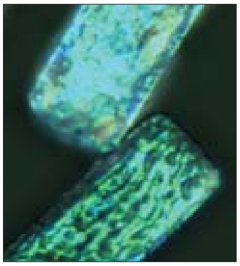
Tanya Z. Kosc



Particle Display Technologies Become E-Paper

Electronic paper is emerging from research laboratories, and technologies based on particle displays are leading the way. Six technologies will be highlighted in order to review the current state of the art.

Envision waterproof, reusable paper onto which new text could be quickly downloaded from any wireless connection as you lounge on a beach. It would be easily legible in the bright equatorial sunlight. There would be no need to carry around a cell phone and squint at its miniature display to read e-mail while worrying about it being damaged by the sand. The paper could be rolled up or folded and stored in your pocket. The display would be thin, lightweight and flexible. Optically, it would be reflective with excellent resolution, high contrast and a wide viewing angle. The technology would be bistable, so that the image need not be refreshed until rewritten, a characteristic that would ensure a low level of power consumption. Today, a number of technologies that aim to create "E-paper"—products which combine the advantages of standard paper with those of electronics—are being studied by researchers in industry and academe.

The world of E-paper is a niche field in information displays, in which the competition is intense and novel technologies abound. The research is interdisciplinary, involving materials science, chemical engineering, electronics and optics. The end-products of competing E-paper technologies differ in appearance, as well as in the physics of operation. The expanding list of technologies being developed with the hope of becoming dominant include: various particle displays; liquid crystal displays; organic light emitting diodes (OLEDS); MEMS-based reflective displays; electro-chromic displays; polymer light emitting diodes; and even an electro-wetting technology. A review of the entire field is beyond the scope of this article because of the variety and number of E-paper technologies. Instead I will highlight some of the most successful and unique examples of E-paper based on the physics of particle displays.

Technology overview

In the race to create a commercially and technologically viable electronic paper, particle displays have several advantages over many other competing technologies. All the current commercial and nearly commercial particle display technologies are bistable, and thus do not require a constant voltage to maintain an image, an important factor that greatly decreases power consumption. A second advantage is that these technologies are all reflective, another characteristic that lowers power requirements in comparison with those of emissive displays such as transmissive LCDs and those made with OLEDs. A typical newspaper has a reflectivity of 50-60 percent, a contrast ratio of less than 10:1 and no viewing angle dependence. Most particle displays are approaching these specifications, with white reflectivities of ~ 40 percent and contrast ratios of between 10:1 and 12:1.

A third advantage of particle displays is that they can be easily manufactured on flexible substrates, or laminated to

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Nick Sheridon, Xerox PARC inventor of electronic reusable paper, and Fereshteh Lesani show off the first roll produced by 3M partners.

Gyricon

them. This task is more difficult with LCDs (which tend to be sensitive to the molecular alignment and the applied electric field, particularly if they are not bistable) and OLEDs. In addition, particle displays do not require processing at high temperatures. Four commercial or nearly commercial particle display technologies have shown the ability to be rolled up into a tube less than a few centimeters in diameter. The thickness of such displays can easily be kept to under 500 µm.

One characteristic that the current crop of E-paper technologies share is a lack is full-color capability. This shortcoming stems from the fact that light reflects or scatters from the particles—often made of white titanium dioxide—that form the display. The use of color filters quickly degrades a display's appearance, because filters can reduce reflectivity by as much as 60 percent.

A brief history of particle displays

The earliest particle display technologies were based on electrophoresis, the motion of a charged particle in an electric field [Fig. 1(a)]. The particles are usually suspended in a fluid, although this is not an absolute requirement. The development of electrophoretic image

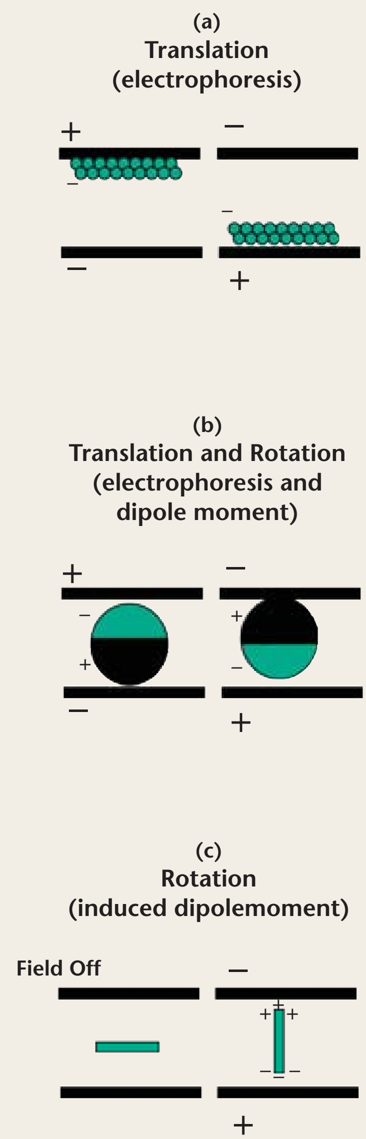


Figure 1. (*Right*) Today there are three basic technologies for particle displays. (a) Most displays are based on translational motion caused by electrophoresis. (b) A particle with an inherent dipole moment and a net charge will display both rotational and translational motion. (c) A charge-neutral particle will rotate when an electric field is applied because the interfacial polarization at the particle and fluid boundary induces a dipole moment.

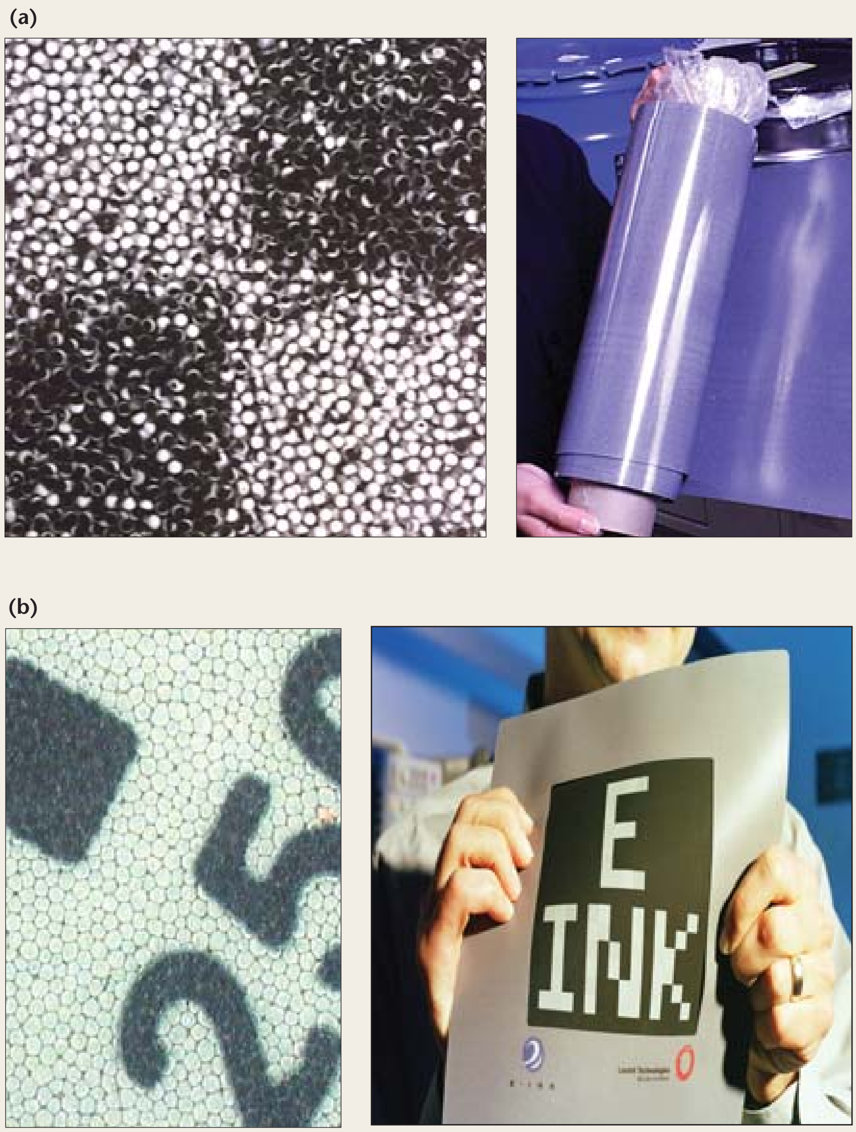


Figure 2. Two electronic paper technologies have been commercialized. (a) Gyricon consists of 75-100 µm bichromal spheres (*left*) that are individually encapsulated in a polymer matrix to form a flexible display (*right*) [Courtesy Gyricon]. (b) E-Ink consists of closely packed capsules filled with micrometer-sized charged particles (*left*) that can be sandwiched between two flexible substrates (*right*) [Courtesy E-Ink Corp].

displays, originally patented in the 1970s,[1] was hindered by particle sedimentation and aggregation until advances in particle encapsulation made it possible to mitigate such problems. In all today's particle display technologies, some form of particle confinement is employed to segregate particles.

Aside from electrophoresis, particle display technologies can be based on particles with a dipole moment, either inherent or induced, which results in rotational motion [Figs. 1(b) and 1(c), respectively]. If the particle also has a net charge, it can undergo both rotational and translational motion [Fig. 2(b)]. Even among particle-based displays, a large number of technologies exist.

Commercial technologies

Two highly visible E-paper technologies have already been commercialized. Gyricon, invented by Nick Sheridon at Xerox PARC, emerged first[2] [Fig. 2(a)]. The Gyricon technology, now being developed by Gyricon Media, a wholly owned subsidiary of Xerox, is a "twisting-ball" display based on individually encapsulated bichromal ~90-µm spheres with oppositely charged hemispheres contained in oil-filled voids in a polymer film. When an electric field is applied, the device relies on both the dipole moment of the unevenly charged particle and the particle's net charge to cause both rotation and translational motion. Bistability ensues because the spheres stick to the conformable (elastomer) capsule walls. If the voltage is too high, a ball may translate faster than it can rotate into the proper position, becoming embedded after a partial rotation only. This effect, which can result in a decreased contrast ratio, can also be used to produce gray levels if the voltage is well controlled. Bichromal balls with different color combinations could be used, but in this case, the displays would still be limited to two colors. Since the Gyricon technology does not have a true threshold voltage, active matrix addressing is used. Typical drive voltages are on the order of 80 V, with response times of less than 300 ms.

Gyricon was largely forgotten until the competing technology, E-Ink, was invented by Joe Jacobson at the Massachusetts Institute of Technology[3] [Fig. 2(b)]. The E-Ink technology, now being developed by E-Ink Corp., is based on the micro-encapsulation of hundreds of micrometer-sized black and white particles, with an opposite charge, suspended in a fluid. Depending on the sign of the applied field, the particles translate toward the top or the bottom of the 50- to 200- mm capsules. Bistability is achieved because the particles stick to each other and to the capsule surface. Grey states are obtained by modulating the applied impulse to a value lower than that required to achieve saturation (the impulse required to bring either all black or all white pigments to the optical plane). Dual color displays can be created relatively easily by placing particles in a colored fluid or by including particles with both different colors and charge. To achieve full color, the E-Ink technology requires use of color filters, although capsules with multicolored, multicharged particles have been conceived. Since E-Ink also lacks a threshold voltage, active matrix addressing must be employed. When an active matrix thin film transistor (TFT) is used, the supply voltage is 3V, with a response time on the order of 300 ms.

Nearly commercial technologies

In 1999, two years after E-Ink Corp. was founded, SiPix Inc., emerged with a display concept that was also based on electrophoresis [Fig. 3(a)]. Instead of segregating charged particles via microencapsulation, SiPix developed the Microcup, a process in which the particle suspension is deposited into 80-160 μm wide compartments embossed into a resin substrate.[4] As in the case of the E-Ink technology, charged particles in the Microcup translate toward the top or the bottom, depending on the polarity of the applied voltage. The compartmentalization of the Microcup substrate is advantageous for producing full color displays, in which each Microcup can act as an individual pixel filled with a particle suspended in red, green or blue fluid. SiPix claims to have devised driving schemes for passive matrix displays, which generally require a threshold voltage, so that their technology can be driven with either passive or active matrix addressing. Response times of 250 ms have been demonstrated using a driving voltage of 20 V.

Another variation on the basic electrophoretic display, the Quick Response Liquid Powder Display (QR-LPD), has been unveiled by Bridgestone Corp. in collaboration with Kyushu University[5] [Fig. 3(b)]. The QR-LPD also consists of black and white particles of opposite charge; in this case, however, they are contained in air instead of in liquid. The words "liquid powder" in the name refer to the fact that, thanks to a chemical treatment, the particles do not pile up when poured (imagine a mound of salt treated so that it spreads out like a liquid). The liquid powder is contained in compartments formed by a ribbed structure on the substrate, with a total device thickness of 290 μm. Since suspending fluid adds drag to particle motion, the lack of such a fluid in the QR-LPD case greatly enhances the speed with which the particles can translate. The QR-LPD response time, on the order of 200 μs, has allowed Bridgestone to venture into video rate applications. The company claims that QR-LPD also has a very sharp threshold, which allows for passive matrix addressing and lower manufacturing costs. The color issue has not been addressed in the literature, but one can imagine that each compartment on the substrate could be filled with red, green or blue particles.

(a)

(b)

Figure 3. The SiPix Microcup (a) and Bridgestone QR-LPD (b) technologies have led to viable devices which are slated for production in 2005. [Courtesy Reiji Hattori, Kyushu University, Japan.]

Emerging technologies

Other E-paper technologies are being developed. Researchers at the University of British Columbia are working with CLEAR Display, a small company that they spun off, to develop the charged liquid electro-active response (CLEAR) technology[6] (Fig. 4). The key to CLEAR technology is total internal reflection (TIR). The front substrate is patterned

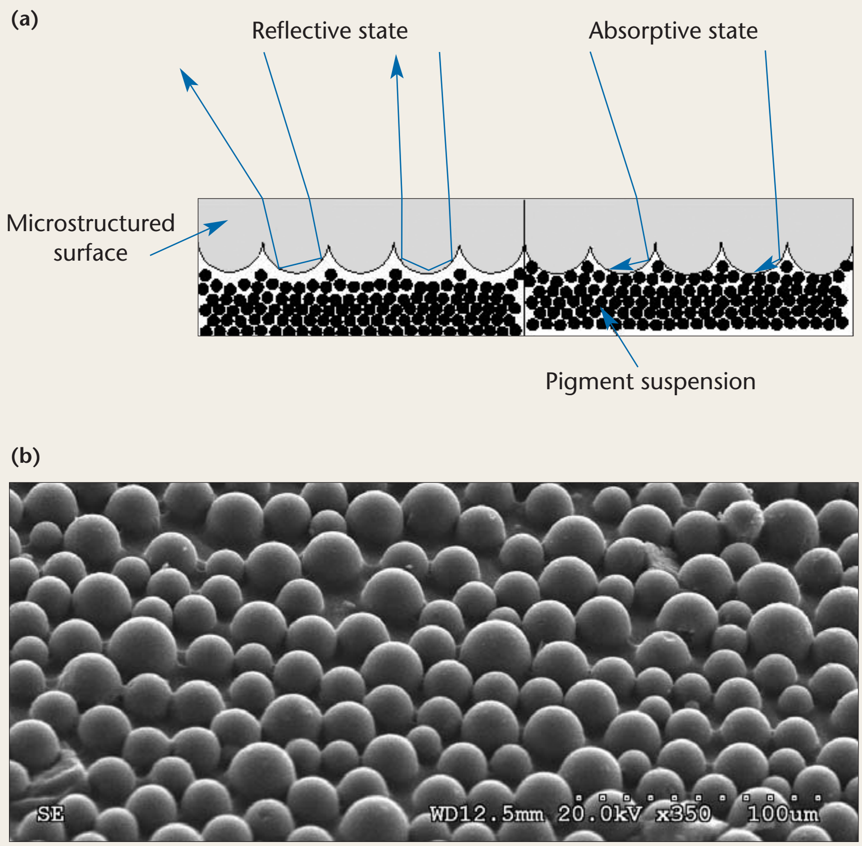


Figure 4. The CLEAR technology is based on the electrophoretic motion of particles, but the use of total internal reflection to produce a reflective state (a) is unique among particle displays. (b) The front substrate of a CLEAR device is patterned with tiny prisms, or hemispheres. [Courtesy Michelle Mossman, University of British Columbia and CLEAR Display.]

with tiny prisms, or hemispheres, which are backed by an electrophoretic dispersion. When a voltage is applied, the absorbing particles migrate away from the surface structures, causing the ambient light to be reflected brightly by TIR. The absorbing particles migrate toward the surface structures when the voltage is reversed, and incoming light is efficiently absorbed, giving this technology much higher contrast and brightness than is the case with a typical particle display. Color can be achieved by use of filters or by filling segmented regions with a colored electrophoretic dispersion. Since the particles must translate only half a micrometer for TIR to take place, response times of less than 50 ms have been demonstrated. CLEAR devices can be easily driven at 15 V, and a bistable device is being developed.

Researchers at the University of Rochester have been developing a unique technology with potential as a particle display that involves polymer cholesteric liquid crystal (PCLC) flakes, aligned in the Grandjean texture, which display selective reflection, an optical property whereby light of a specific wavelength and polarization (circular) is reflected from the surface of the flake (Fig. 5). As in the case of the previously described technologies, the PCLC flakes are dispersed in a suspending fluid, but here, they are neither spherical nor charged. The particles do not display translational motion due to electrophoresis. Instead, the interfacial polarization at the flake-fluid boundary induces a dipole moment upon which the applied electric field acts, causing flakes to reorient from a bright, reflective state to a dark state.[7] PCLC flakes can be produced to reflect any desired wavelength, and to act on either right- or left-handed circularly polarized light. Due to the selective reflection, color filters would not be needed. Additional features could be included in displays because of the inherent ability for PCLC flakes to discriminately reflect one handedness of circularly polarized light. Polarization discrimination simplifies the ability to create three-dimensional displays and allows security features, such as identification and anti-counterfeiting, to be easily included. No other particle display technology can accomplish polarization without using polarizing filters, which add to manufacturing cost and detract from appearance.

A PCLC flake display would require either micro-encapsulation or the use of a microstructured substrate to segregate and order particles and to develop a mechanism for bistability. Current PCLC flake test devices can be driven with less than 5 V and response times on the order of 300 ms have been demonstrated. As with most other particle display technologies, there is no sharp threshold voltage and active matrix addressing is required.

Current and potential products

Every few months, a new press release documenting the progress of E-paper appears. In recent months, E-Ink Corp. announced collaborations with Neolux Corp. and Midori Mark, both manufacturers and distributors of advertising and promotional displays, to manufacture and market Ink-In-Motion electronic paper displays for the retail point-of-purchase market. These products are likely to compete directly with Gyricon's SyncroSign family of displays. Both products are battery-powered, while Gyricon's SyncroSign already has the option of being used with the SignSync software for the creation, scheduling and wireless transmission of messages.

E-Ink has different partners for additional products. The company is working with Royal Philips Electronics and Sony Corp. to enter a different display market and produce a first-generation e-book reader, Sony's Librie, available only in Japan. Toppan Printing Co. Ltd. has partnered with E-Ink to manufacture and market segmented e-paper display modules (tiles) that consist of the E-Ink Imaging Film laminated onto a printed circuit board. Up to 90 tiles can be driven with the existing controller to produce large area signs that will target system integrators of public and transportation signs.

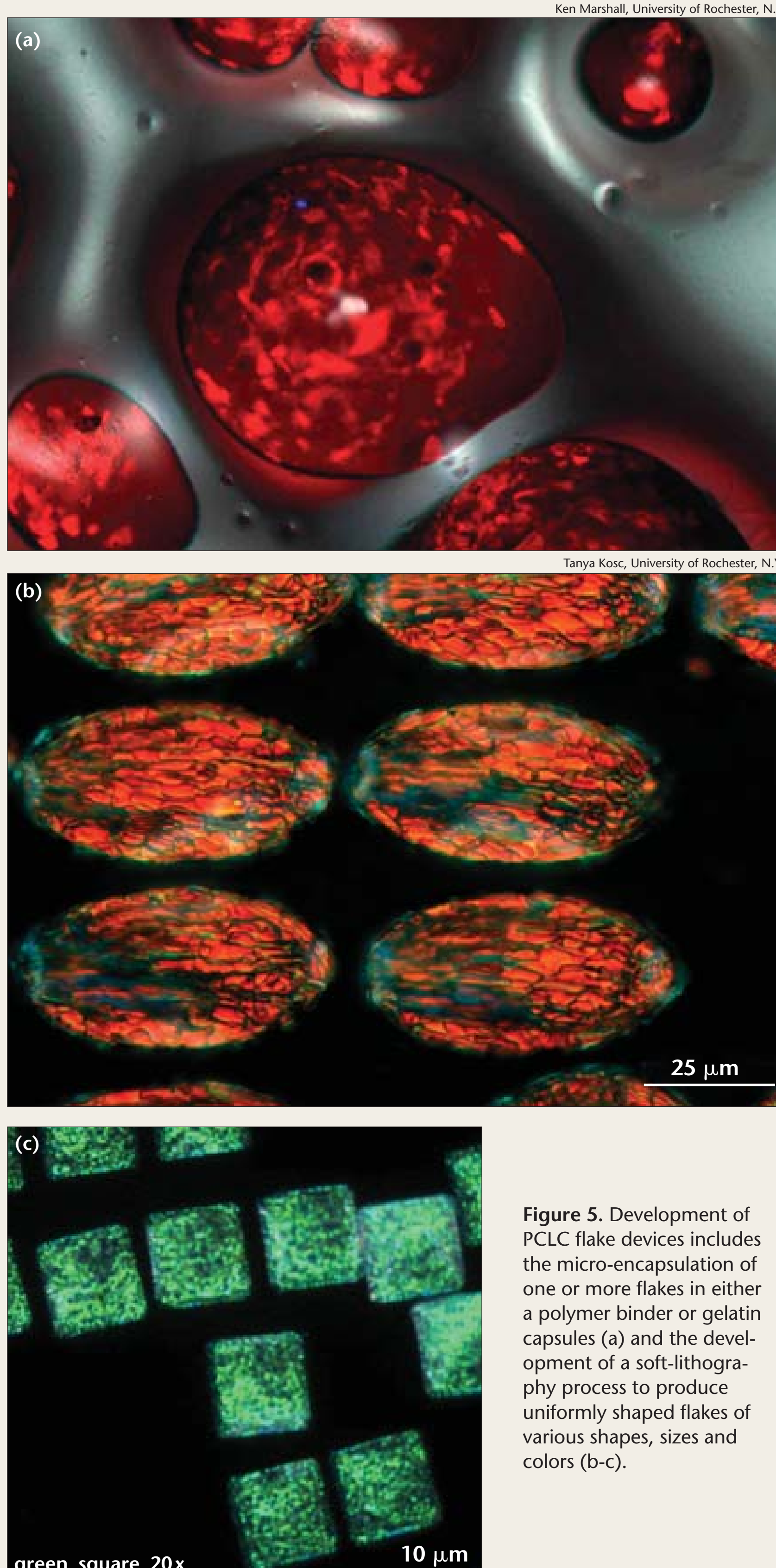
In the fall of 2004, Bridgestone announced that the Quick Response Liquid Powder Display will enter the market with ultra-thin electronic price tags, and there are plans to start mass-producing the devices by the end of 2005. The first electronic price tag product will have a screen size of 4.5 inches and thickness of 1 mm. SiPix has entered into an agreement with Philips Electronics (via Polymer Vision, a venture in the Technology Incubator) to develop a flexible electronic display, but no commercial product is yet available. In the meantime, technologies like CLEAR displays and the PCLC flake/host fluid suspensions will continue to be developed.

There are many potential markets for e-paper into which any one of the particle display technologies could eventually enter. Imagine: automobile dashboards; heads-up displays; personal data assistants; identification cards displaying personal information; vehicle camouflage; environmentally robust switchable "paints" or conformal coatings; switchable "smart windows" for energy or privacy control (Research Frontiers Inc has already licensed its technology to window manufacturers); and even fabrics that make a fashion statement. I look forward to reading the latest headlines on my reusable e-paper some time in the future.

Tanya Z. Kosc (tkos@lle.rochester.edu) is a research associate at the Laboratory for Laser Energetics at the University of Rochester (www.lle.rochester.edu).

OSA Member

Ken Marshall, University of Rochester, N.Y.



Tanya Kosc, University of Rochester, N.Y.

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Figure 5. Development of PCLC flake devices includes the micro-encapsulation of one or more flakes in either a polymer binder or gelatin capsules (a) and the development of a soft-lithography process to produce uniformly shaped flakes of various shapes, sizes and colors (b-c).

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