L-1: *Late-News Paper:* Conformable-Polymer Dispersed Liquid Crystals (C-PDLC) Displays With Indefinitely Captured Form

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Abstract
We have developed a conformable-polymer dispersed liquid crystal (C-PDLC) by processing a PDLC material between conducting indium-tin-oxide (ITO) coated polyethylene terephthalate (PET) substrates above the glass transition temperature of the PET. After first fabricating a PDLC between ITO/PET substrates at room temperature, the display is then molded to conform to a particular template, heated above the glass transition temperature, and then allowed to cool back to room temperature where it is then released from its template. Using this process the PDLC display remains indefinitely conformed while retaining its optical functionality. We present a comprehensive study on the optical performance of these conformable displays, the processing steps necessary for fabrication, and the issues associated with the conducting substrate technology processed above the glass transition temperature.

1. Introduction
We live in a display-centric world. The time has come where we are seeing far-reaching prototypes and products that utilize plastic substrates that are ultimately lighter, thinner and more robust than their glass-based display counterparts, and the promise of form, fit, and function is starting to be realized. Plastic substrates are an enabling technology for many display product categories, such as smart cards and electronic paper. The outstanding issues with plastic substrate technology are two fold: first, processing temperatures must remain low limiting the deposition techniques required for indium-tin-oxide (ITO) and thin-film-transistors (TFTs). Secondly, the amount of strain that the deposited layers can withstand before catastrophic failure is relatively small. These issues have stimulated some basic research on the mechanics of ITO and conventional TFTs on plastic substrates [1,2] and research efforts on conducting polymer substrates [3] and organic TFT technology [4], which are more compatible to low temperature processes.

Plastic displays that are flexible and conformable will pave the way for truly creative applications such as displays integrated into your clothing, displays that you can pull out of our pocket and unfold into a >15 inch-diagonal screen, a display that unrolls across a large conference table, or a display that unrolls out of your pen. These visionary concepts are not too far away from reality. Conventional thinking regards the role of a conformed display as one that is fabricated and then secured to a curved surface. What if a display could be analogous to 'heat-shrink' in electronics? With such a technology, one could envision a number of new application areas. Since indium-tin-oxide (ITO) on PET substrates can withstand moderate mechanical and thermal shock, there is potential to build a display, conform it to a given template, heat it above the glass transition temperature of the PET and slowly cool back to room temperature, resulting in a display that functions and retains the template form indefinitely.

In this contribution, we present our work on conformable-polymer dispersed liquid crystals (C-PDLCs) using this approach and the key issues associated with their processing and operation, and their ultimate limitations. Conforming the PET substrate to a curved surface and processing the display above T_g effectively removes the residual stress in the substrate. Since the stress in the ITO film is a result of stress-transfer from the substrate, relaxation of the stress in the substrate results in a relaxation of the stress in the film. We have chosen PDLC materials to work with in this study because of their robust nature. Figure 1 depicts an illustration of a C-PDLC. In the off state when no voltage is applied, the droplets of liquid crystal are randomly oriented, and the index of refraction of the liquid crystal droplet (some combination of the ordinary, n_o, and extraordinary, n_e, index of refraction) is different from that of the polymer matrix n_p. This creates an opaque appearance. In the on state when a sufficient electric field is applied to align the symmetry axes of the liquid crystal droplets (bipolar droplets), the ordinary index of refraction, n_o, matches that of the polymer n_p and the display becomes transparent. We have utilized polymer-dispersed liquid crystals (PDLC) for this study [5], but there is no reason why this approach cannot be used in other types of display materials that can withstand the process temperatures, such as polymer dispersions, electrophoretics, and gyricon, for example.

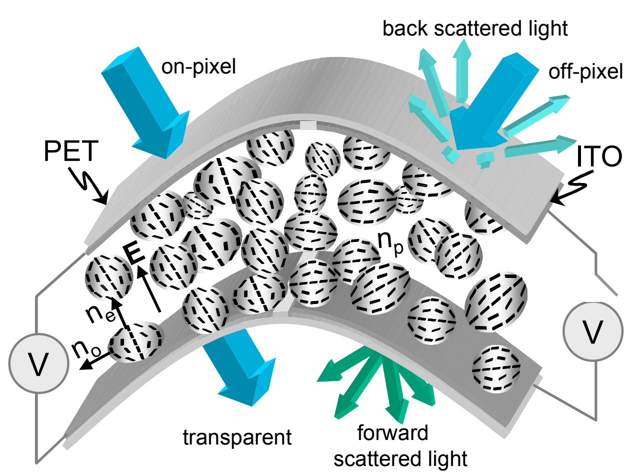

Figure 1: An illustration of a conformable PDLC display in the on-state (left pixel) and the off-state (right pixel).

2. Sample Fabrication
A commercial mixture of the reactive monomer (PN393) and liquid crystal (TL205) was used to create the electro-optic medium; both components are commercially available from *EM Industries*. This material was processed on 1-inch by 5-inch PET/ITO or PEDOT:PSS/PET substrates using 10 µm spacers, vacuum pressed, and then photopolymerized with an ultraviolet blanket exposure process. The PET/ITO substrates are commercially available from *Southwall* and the conducting

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polymer substrates made from PEDOT:PSS/PET [6] are commercially available from *AGFA*. As expected, the conducting polymer PEDOT:PSS on PET is much more stable than the ITO on PET when continual bending experiments are performed; however, its resistance is higher and its transparency is lower than the ITO/PET samples. At this point, there is nothing unusual about the PDLC process except that we are using plastic substrates rather than glass. We have conformed the display around a 1-inch hollow pipe to create a spiral or interlaced it between two pipes to create a sine wave deformation or used a hemispherical type surface as shown in Figure 2. While conformed to this configuration, we have inserted it in the oven at 90°C (above the glass transition temperature of the PET substrate) for one-hour. The oven in Figure 2 is represented as a box. The configuration was then removed and allowed to cool back down to room temperature where the template was removed. We have performed studies on the degradation of the PDLC material and PET/ITO substrates and found that degradation occurred at >200°C for both materials, in air. Using a mass loss experiment, degradation is defined as the temperature where the material losses 5% of its mass. Since we are well below this temperature we expect no appreciable degradation.

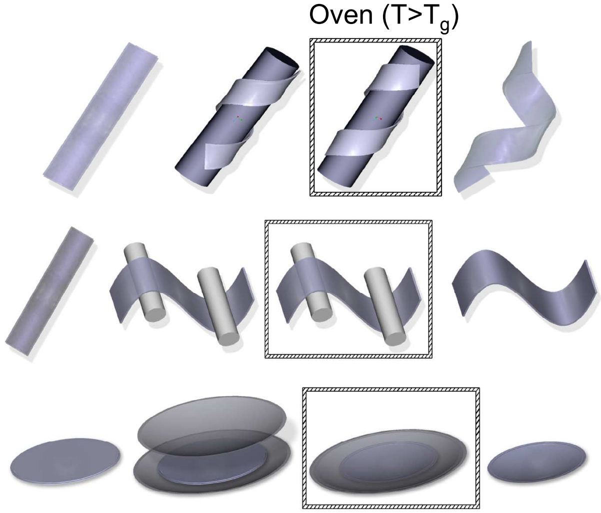

Figure 2: Examples of conforming templates. A spiral (top), a wave (middle), and spherical cap (bottom). The box in the figure represents the oven above the glass transition temperature of the PET.

Figure 3 shows photographs of actual conformable samples that we have fabricated of dimensions 1”×5”. All samples in Figure 3 were conformed at room temperature, processed at 90°C for one hour and then cooled down to room temperature. In Figure 3 (a), we demonstrate the conformal nature of one sheet of PET/ITO without any display medium. The control sample (unconfirmed) is shown in Figure 3(b) in both the off (left) and on states (right). Figure 3(c) and (d) show conformed samples in the off and on states with helical and wave-like conformance. We have only been successful thus far in making spherical cap conformations shown in Figure 2 (bottom) on very small radius of curvature templates. For large radius of curvature in this biaxial situation, the PET often creases and the display is non-usable. More work is in progress regarding conforming in two directions.

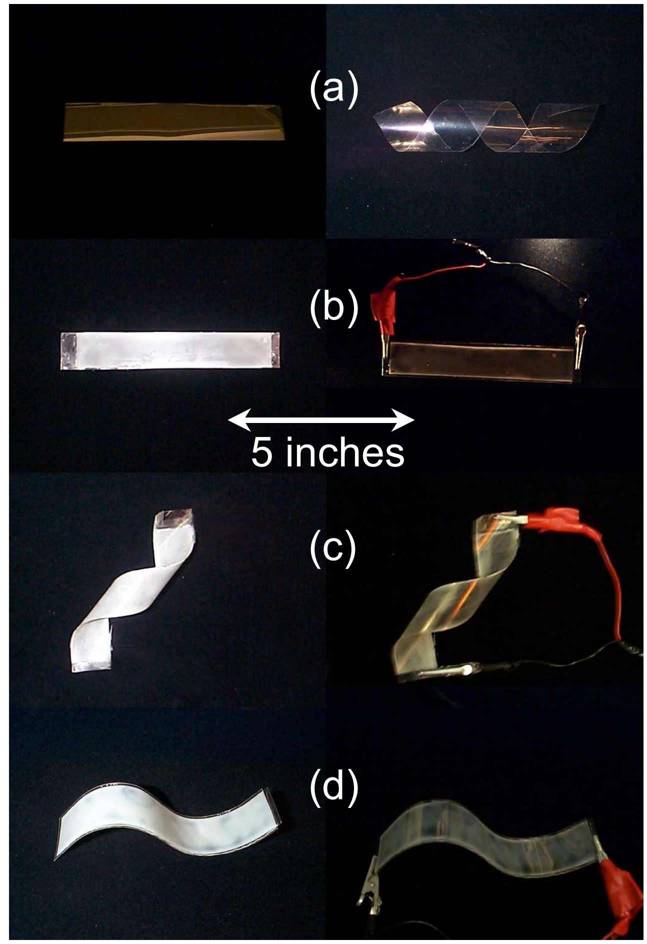

Figure 3: Actual conformed samples are presented. A single sheet of PET/ITO is shown in (a) and the control PDLC samples are shown in (b). A helical sample and wave-like sample are presented in (c) and (d) respectively. The left column shows the voltage off state and the right column shows the voltage on state for (b)-(d).

It is clear from Figure 3 that the conformal nature of the display is permanently captured and that the PDLC material is still switchable even after the fabrication process.

3. Results

To successfully implement the conformal process described above, there are a number of issues that arise that need to be addressed on the substrate and the electro-optic material level. Figure 4 depicts a schematic illustration of the conformed PDLC display. When using ITO/PET substrates, the ITO is in tension on one substrate, which can result in cracking when strain is above threshold, and in compression on the other substrate, which can result in delaminating and/or cracking when strain is above threshold as shown in Figure 4 [1]. When implementing the PEDOT:PSS/PET substrates, cracking is not an issue. The PDLC material is also subjected to strain and therefore we need to understand how it responds to the conforming process.

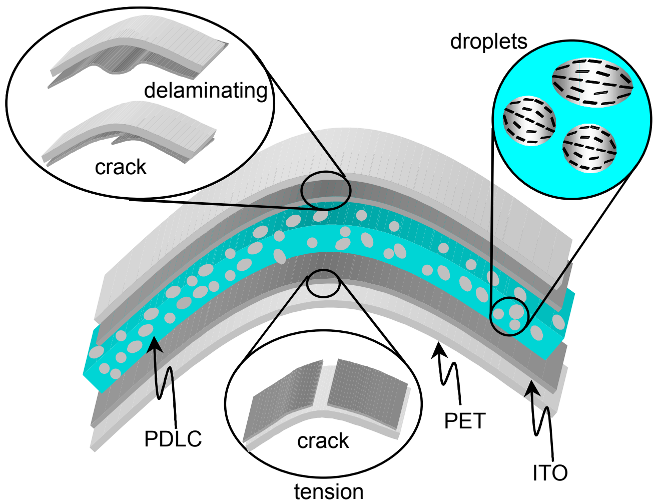

Figure 4: An illustration of a conformable PDLC display showing that the ITO/PET substrates can respond to strain in different ways. On the top substrate, the ITO is in compression and on the bottom substrate the ITO in tension. In compression both cracks and delaminating can occur and in tension cracks can occur if the strain is above threshold.

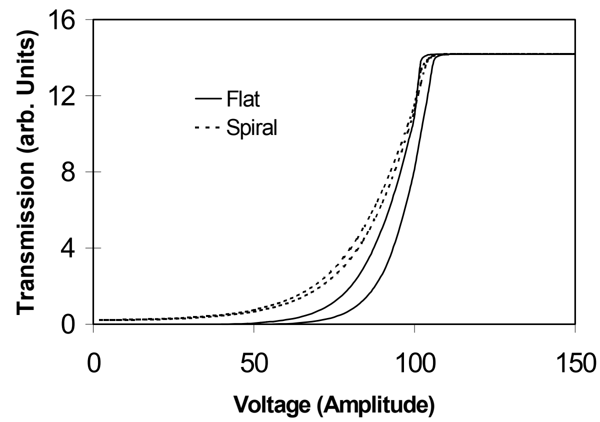

Figure 5: The transmission versus voltage curve for the unconfirmed (flat) and conformed (spiral) PDLC sample.

3.1 Electro-optic Performance

We have evaluated the electro-optic performance at room temperature before and after the conformal process. The transmission-voltage curve is presented in Figure 5 for a ITO/PET sample that was conformed around a 2" pipe. The results are very interesting for several reasons. There are a few obvious features that can be easily seen in Figure 5; (1) lower threshold voltage for deformed displays; (2) significantly less hysteresis for the undeformed sample; and (3) lower contrast for the deformed sample. First, the conformed display has a lower threshold voltage, V_{th}~60 volts, as compared to the threshold voltage of the unreformed sample, V_{th}~75 volts.

It should be made clear that this is the same sample, measured before heating and deformation and then again after. Second, the hysteresis is much smaller for the conformed sample at 50% transmission, ΔV_{50}=1.4 volts, as compared to the unconformed sample, ΔV_{50}=4.4 volts. The contrast ratio decreases in the conformed sample. Using a HeNe laser and a silicon detector (diameter= 1 mm) positioned 10 cm away from the PDLC sample, the contrast ratio is ~300:1 for the undeformed samples and ~20:1 for the conformed sample. We believe that the strain introduced by conforming the display can bias the droplets director configuration and enable them to switch at lower voltages, which would also explain the reduced hysteresis, and the undesirable feature of lowering the contrast. In principle, the PDLC would be in the neutral plane, but the heat treatment certainly alters the stress distribution. At this point, this is our only explanation and it seems to be consistent with all of the differences between the conformed and flat sample. Current investigations and modeling efforts are underway to measure the contrast ratio, the threshold voltage, and the hysteresis as a function of curvature.

3.2 Substrate Performance

To successfully implement the conformal process for a workable display, the PET/ITO substrates are key. There are many questions that arise regarding the resistance of the ITO on PET. The major one is how will ITO resistance withstand the strain introduced from the template and how do temperatures that exceed the glass transition temperature of the PET influence it. To gain an understanding of what happens to the ITO above the glass transition temperature, we have performed scanning electronic microscope studies on ITO/PET. After the substrate was conformed to a 1 cm bend to introduce both tensile and compressive strain as shown in Figure 6. The samples were then processed above T_g for one hour and allowed to cool so that they retained the shape of the template indefinitely. The radius was 5 mm, which corresponds to ~2% strain in our films. This value of strain introduced cracks in both compressive and tensile strain as is clearly evident from Figure 6. When cracking occurs there is a large jump in resistance and the display will no longer respond to applied voltages [1]. In our samples shown in Figure 3, we have not introduced high strains to avoid cracking and catastrophic failure. Our spiral samples were wrapped around a 25 mm cylinder. Cracking is not a problem in the conducting polymer samples using the PEDOT:PSS/PET substrates [3].

In order to quantify the extent of damage to the ITO above Tg, we have performed *in situ* stress strain experiments where the resistance is simultaneously measured. The first measurement that we performed was a uniaxial strain measurement at temperatures above the glass transition temperature of the PET. Figure 7 shows the resistance as a function of strain both above and below the glass transition temperature of the PET.

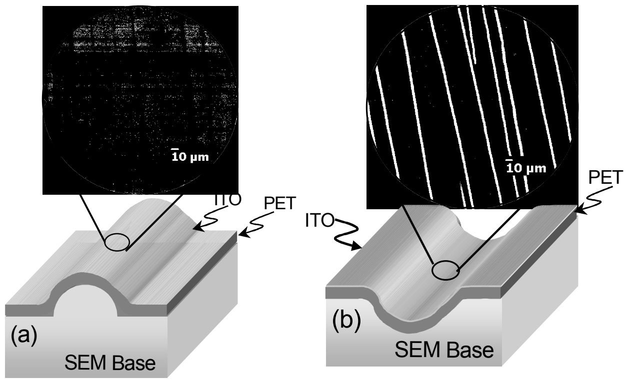

Figure 6: Scanning electron microscope images of ITO in tension (a) and compression (b). The radius of the deformation was 5 mm.

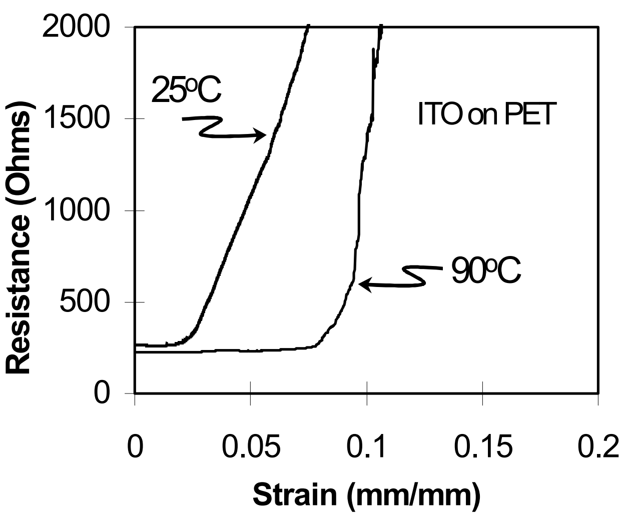

Figure 7: Resistance versus strain for ITO/PET samples deformed in uniaxial tension above and below Tg. The gauge length of the samples was 7.5mm and the crosshead speed 0.1 mm/minute.

It is interesting to note that above the glass transition temperature the ITO takes substantial strain before the resistance rapidly increases. There are many ways in which to make conformable displays. In addition, the processing techniques are critical. The results are shown in Figure 7 for films investigated above and below the T_g. Below T_g the resistance increased rapidly above a critical strain of approximately 0.02 (2% engineering strain). As reported previously [1] the critical strain is related to the onset of cracking in the ITO layer and this is consistent with the electron microscopy studies reported in this paper and shown in Figure 6.

Above T_g the critical strain was much greater approximately 0.08 (8% engineering strain). This large increase in critical strain may be due to relaxation of stress in the substrate during the test or a consequence of increased crystallinity in the PET substrate, which enhances the interfacial shear strength of the ITO/PET interface [7]. Our original application area of conforming a display to a given template and then annealing it with a temperature above T_g to capture its form indefinitely is intriguing from the applications standpoint of retrofitting displays into various forms in the field. However this is limiting since you will be 'working-on' the 25°C curve in Figure 7, independent of our conforming temperature since strain introduced at 25°C. It may be possible to utilize the improved durability of the ITO layer above T_g to fabricate conformal displays with very small radius of curvature features by processing in the following way: (1) heat flat above T_g; (2) conform heated display to template; (3) hold display and template at temperature for one hour; (4) cool display and template; and (5) remove conformal display from template.

This process would enable you to 'work-on' the 90°C curve in Figure 7, however it is a bit more limiting in the sense that the process must be carried out at elevated temperatures, probably at the plant, whereas the former technique presented in this paper has potential to be performed on site using a heat gun for example. The PEDOT:PSS/PET substrates may also be particularly suitable for fabricating small radius of curvature features. Deforming PEDOT:PSS/PET substrates in unixaial tension at room temperature resulted in a 10% shift in resistance at a strain of 0.2 (20% engineering strain). We are currently pursuing this alternative in more detail.

4. Summary

This is certainly the first paper that presents data on the effects of conformal displays from the substrate and display materials perspective. It is also a new way to think about conformable displays that permanently deform and that can be molded to retrofit many shapes and curves. We believe that this concept in not limited to PDLC materials, but also can be used for electrophoretics, gyricon, and other liquid crystal/polymer dispersion materials.

5. Acknowledgements

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