Active Matrix Polymer Cholesteric Liquid Crystal Display (May 2008)

G.B. Myhre, J.P. Cox, K.L. Marshall, T.Z. Kosc, C.A. Fromem, S.D. Jacobs

***Abstract*—Polymer cholesteric liquid crystal display technology has been demonstrated previously on single pixel monolithic displays at the University of Rochester's Lab for Laser Energetics. Mass reorientation of PCLC flakes in a variety of host fluids has been modeled and observed. However, a pixilated PCLC display has never been demonstrated. The motive of the project was to create a prototype pixilated PCLC display in order to demonstrate the commercial viability of the technology. An active matrix back plane was designed, fabricated, tested, and incorporated with the existing PCLC display technology. The resulting display showed strong isolation between pixels with negligible cross talk.**

***Index Terms*—Polymer Cholesteric Liquid Crystals, Active Matrix Displays**

I. Introduction

Research and investment in particle based displays has expanded recently as flexible substrate technology has become more appealing and manufacturable. Using an electric field to control the motion of particles has been explored since the early 1970s. Electrophoretic displays were one of the primary contenders to replace cathode-ray tube displays until liquid-crystal technology became dominant in the 1980s. Particle displays are now regaining attention as flexible low power display development gains momentum.

The University of Rochester's Lab for Laser Energetics (LLE) has developed a unique display technology based on polymer cholesteric liquid crystals (PCLCs) flakes. [1] PCLCs have been traditionally used in passive applications for their reflection of specific wavelengths and polarization characteristics. At LLE the rotation of PCLCs suspended in a host fluid has been explored. A vertical electric field induces a dipole moment on the flake due to Maxwell-Wagner polarization, which causes the flakes to reorient its longest axis parallel to the electric field.[2] It has been shown that flakes suspended in a host fluid will reorient in as short as hundreds of milliseconds under an applied bias as small as 5 mV/μm.

All previous demonstrations of PCLC display technology have been on monolithic 'single pixel' devices. The motive of the project is to pair a custom active matrix backplane and the current PCLC technology to create a functional prototype PCLC display that has an array of pixel units that can be individually addressed. The first generation devices have been processed on silicon with the intention of moving the technology to a glass or flexible substrate platform for future iterations.

II. Polymer Cholesteric Liquid Crystal Fundamentals

A. *Cholesteric Liquid Crystals*

Cholesteric liquid crystals (CLCs) are a unique type of liquid crystal that can selectively reflect a specific bandwidth of light. The long range order of the molecules is defined by the director. The director lies in the plane of the LCs and twists in a helical fashion around the vector normal to the plane of the LCs. The distance it takes for the director to rotate 360° is defined as the pitch length (p) of the material and determines what wavelengths the CLC reflects. The direction of rotation of the director determines the handedness of the material. Fig 1.1 shows a diagram of a Cholesteric LC. PCLC flakes are made by heating the polymer CLC to its cholesteric state and then cooling it below its glass transition temperature, (T_g) fixing the internal orientation of the molecules.

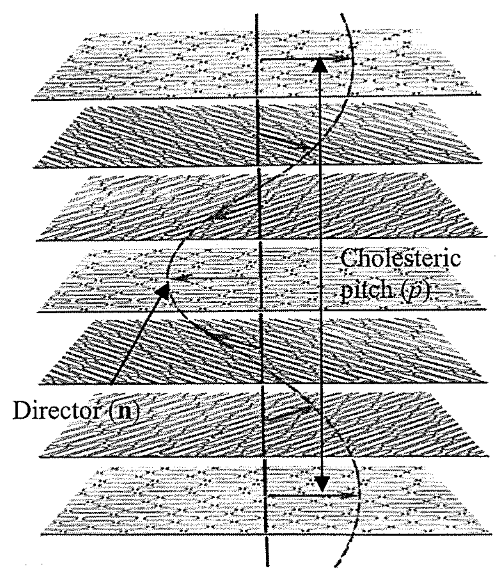

Fig 2.1 A diagram of a left-handed cholesteric LC of pitch p. The director, **n**, is illustrated by the red arrows.

B. *PCLC Flake Reorientation*

PCLC flakes can be suspended in a moderately conductive host fluid such as propylene carbonate. A vertical field is applied to the suspended flakes causing them to reorient to the plane of the electric field. Fig 1.3 shows the change in orientation. Rotation is due to the vertical field, which induces a dipole moment on the flake. The dipole is

brought about by the difference in the conductivity and dielectric constant of the flakes and host fluid. [3]

The rotation of the PCLC flakes cause dramatic drop in reflectivity. Fig 1.4 shows a patterned ITO substrate before and after the rotation of the flakes.

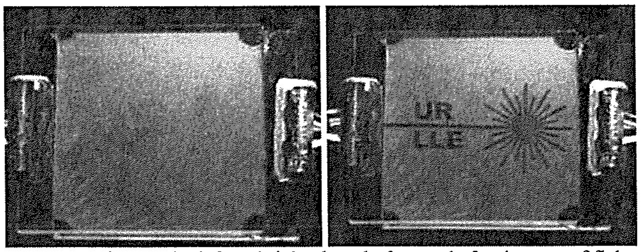

Fig 2.2 The left and right show before and after images of flake rotation. The "UR LLE' image is formed by patterning the ITO on the glass substrate.

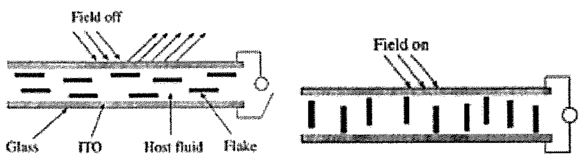

Fig 4.1 Example of the rotation of PCLC flakes suspended in a host fluid when a vertical field in applied. The vertical field is created by applying a bias to one plate of the indium tine oxide (ITO) substrate and grounding the second.

III. Display Addressing Schemes

In a pixilated display there are 3 main ways of addressing individual pixels: direct, passive matrix, and active matrix addressing.

A. *Direct Addressing*

In a direct addressing scheme each pixel is controlled by its own individual control signal. In a display with $m \times n$ pixels, the display would require $m \times n$ control signals. For anything but the smallest displays this scheme is considered to be inefficient use of I/O and physical space.

B. *Passive Matrix Addressing*

Passive matrix addressing can address $m \times n$ pixels with only $m + n$ control signals. The scheme divides the incoming signal into a select (row) signal and a video (column) signal. Each row is addressed one at a time by raising the select signal voltage. Each pixel in that row is then individually addressed with a video signal. Passive matrices have no active elements and therefore each pixel element needs bi-stability in order for it to maintain its image.

C. *Active Matrix Addressing*

Active matrix addressing uses the same number of control signals as a passive matrix display. The main difference is that each pixel is isolated individually through an active component. The active component is usually a thin film transistor in display devices. The addressing is done one row at a time and starts by raising the signal voltage on the address. The signal voltage is connected to the gate of each transistor and turns the device on. Each pixel in the row is then addressed by its individual video signal. The signal voltage is then dropped low again isolating each pixel. Each element has a built in capacitance that can maintain the voltage applied by the video signal until it is addressed again. The speed at which each row can be addressed and the number of rows determines the total scanning period of the display. The inverse of the scanning period is the maximum refresh rate of the display. The scanning period must be less than the time it takes for the capacitance on each device to decay in traditional LC Displays. The quasi-bistability of PCLC displays allows for moderately long delay (<1 min) between addressing.

IV. NMOS Active Matrix Backplane

A. *Active Matrix Design*

The active matrix back plane design is based off of a donut gate DRAM cell. Similar to DRAM, the basic cell is a parallel plate capacitor with one plate being an aluminum pad that is addressable through an active device and the second plate is common ground to all of the pixels. The donut gate transistor maximizes the effective device width and also allows for square or rectangular pixels that can easily be tiled to create displays of various sizes. The technology and process flow for the devices is loosely based on the NMOS portion of the SMFL CMOS technology, which uses lambda of 5 μm. Fig 4.1 shows both an aerial and cross-sectional diagram of a single pixel. The dimensions drawn are for a 635 μm square pixel. A variety of other pixel sizes where also included in the design ranging from 250 μm to 5 mm. Fig 4.2 shows an array of 250 μm pixels prior to aluminum deposition.

A unique feature of the device is the SU-8 3050 well layer. It is designed to be 100 μm thick and have a minimum line width of 20 μm. It is the last processing step before dicing the wafer and is critical because the high aspect ratio 4.5:1 "wells" are difficult to resolve and the epoxy based SU8 resist cannot be reworked. The SU-8 wells serve a dual purpose in the device. First, it determines the gap height between the aluminum and the ITO glass which must be thick enough to allow the flakes to rotate, but thin enough to allow for minimum field strength of 50 mV/μm. Secondly, the wells physically isolate the fluid and flakes in each pixel. This is crucial because both the fluidic motion of the pixels during rotation and the fringing electric fields during addressing can cause the flakes to laterally migrate out of "on" regions, which effectively destroys the device. Metrology of the SU-8 layer was done using a Zygo white light interferometer and measured the SU-8 well to be 89.6 μm thick.

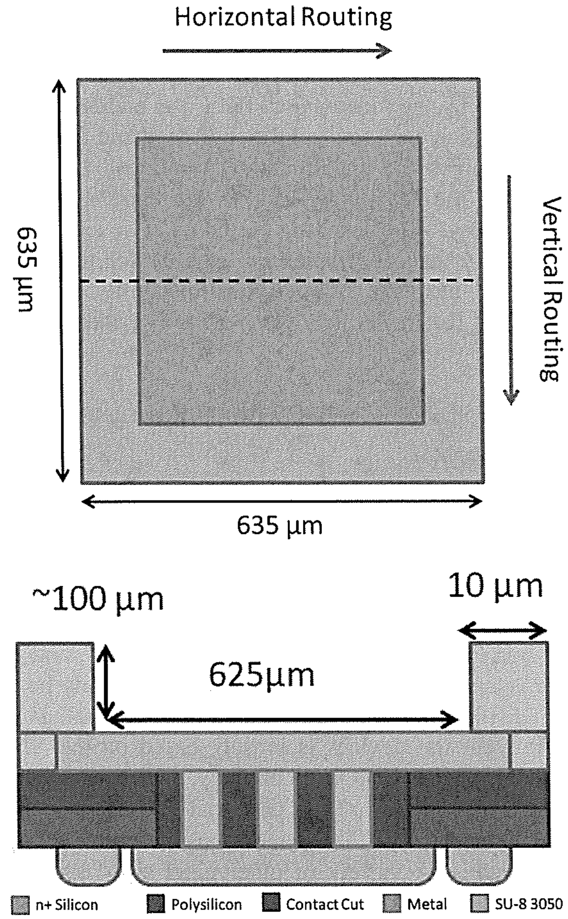

Fig. 4.1 Layout (Top) and cross-sectional (Bottom) views of a single pixel are shown. The layout shows the donut shaped gate, which allows for the maximum effective device width.

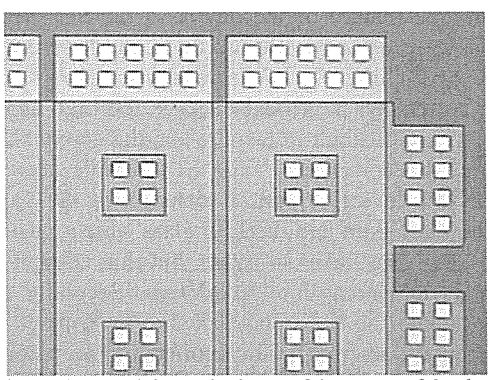

Fig. 4.2 (left) A micrograph image is shown of the corner of 6 x 6 array of 250 µm pixels. The photo was taken directly before aluminum deposition and shows the polysilicon vertical routing in pink. The green portions show the active device area. The horizontal routing in n^+ silicon can only be seen under higher magnification.

B. Active Matrix Electrical Testing

The devices were electrically tested prior to the SU-8 well layer being patterned. Fig 4.3 shows a threshold voltage of 0.6 V. An I_{DS} versus V_{DS} plot with 0.5 V increments of V_{GS} is shown in Fig 5.4. The I_{on} / I_{off} of the device is greater than 5 decades, with a peek drive current of about 25 mA. The donut gate device has a gate length of 20 µm and an effective width of 2300 µm, which gives roughly 10.9 µA per micron of device width.

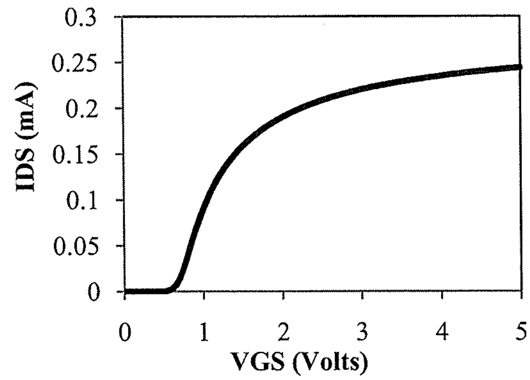

Fig 4.3 V_{GS} versus I_{DS} for the same 635 µm test pixel. The plot shows a threshold voltage of approximately 0.6 V.

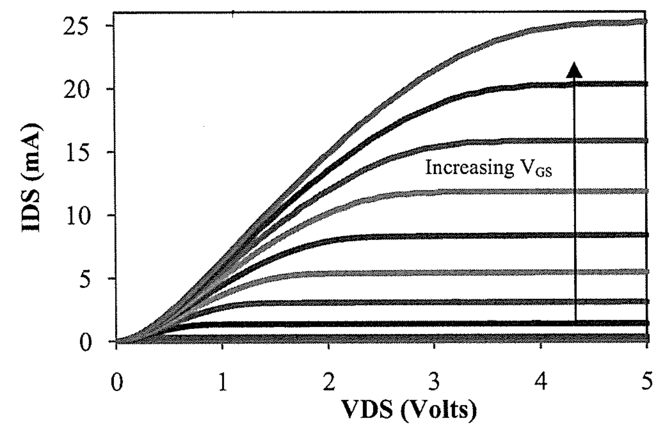

Fig 4.4 V_{DS} versus I_{DS} plot with V_{GS} stepped in 0.5 V increments for 635 µm square test pixel. The device has an I_{ON} / I_{OFF} > 5 decades.

V. Display Assembly and Results

A. Display Assembly and Packaging

Final devices were assembled by dicing the wafers into their individual display components. The display itself is assembled by filling the SU8 wells with propylene carbonate and a 1-5% concentration by weight of commercial freeze fractured flakes. The display is then sealed by bonding glass with an ITO film onto the top of the display using a UV curing epoxy. The device is sealed with epoxy along the edge to prevent contamination and leaking of the fluid. A 64 x 64 array of 635 µm pixels at this point is shown in Fig 6.1. The voids in the display are caused by air bubbles being trapped in the SU-8 wells when the display is sealed.

The bottom image in Fig. 6.1 shows the same display without a circular polarizer. PCLC technology is designed to not need a polarizer however limitation of the active matrix technology requires one as discussed in Section 7.

Final devices were mounted to custom PCBs that include simple drive circuitry capable of addressing sections of the display. They are attached to the board using two-part epoxy and then electrically connected using colloidal silver paint. The driver boards are not capable of addressing individual pixels, however sections of the display can be addressed and

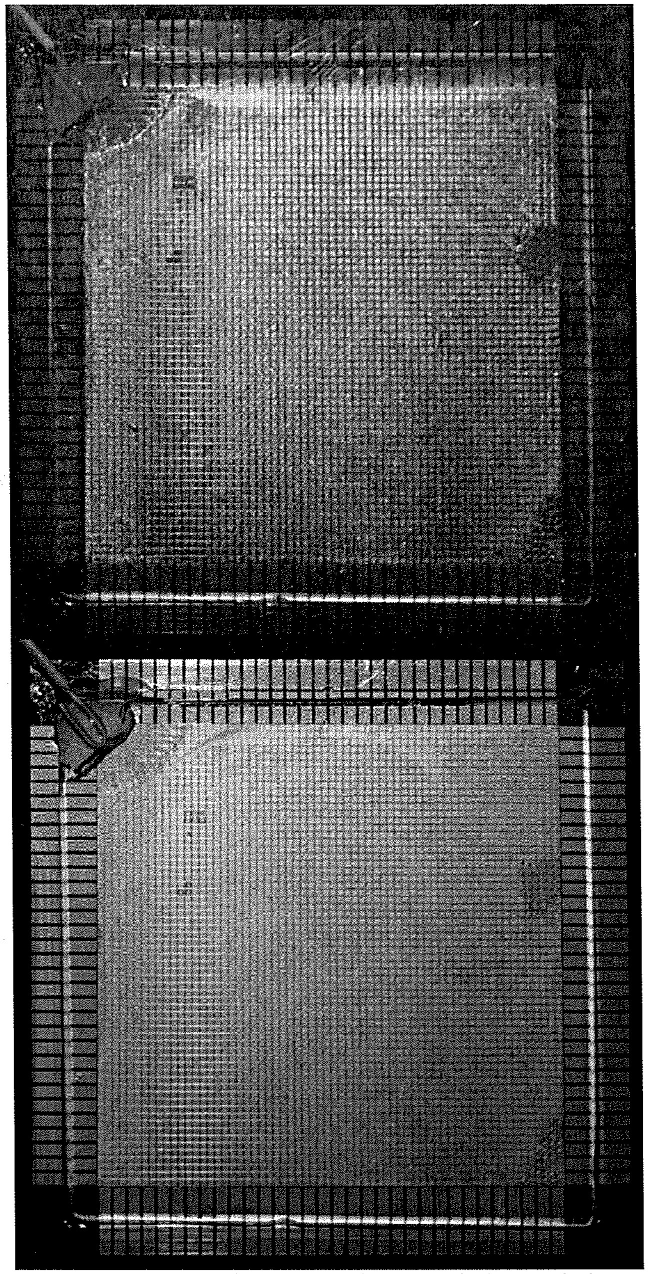

Fig 6.1 The top and bottom pictures above show a 64 x64 635 µm pixel display with and without a right-handed circular polarizer. The marks in the display are due to air being trapped in the wells when the display is sealed.

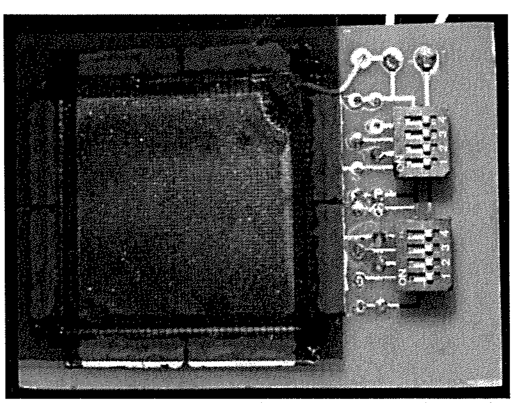

Fig 6.2 The same display shown in Fig 6.1 now mounted to a PCB driver board. Biasing is done through pull up circuits which are connected to sections of aluminum contact pads.

checkerboard patterns can be displayed. Fig 6.2 shows the same display mounted on a custom PCB board.

B. Display Results

Using weak biasing signals of 2.5 – 4 V_{p-p} 100Hz AC, videos of flake rotation were recorded under different magnifications. Fig 6.3 shows the center 635 µm pixel being biased with a 2.5 V_p-p 100 Hz signal under 30x magnification. The flakes rotated in approximately 6 seconds. Much faster response times can be obtained by using larger drive voltages (<1 second). The 3.5% PCLC flake density by weight produces an image with strong contrast.

Fig 6.4 shows the border of two 635 µm pixels under 100x magnification. The flake density is very low in this display and allows for each flake to be seen rotating individually. The right side of the image shows the majority of the flakes rotating while the left side remains unchanged. This demonstrates very strong isolation between pixels. Meaning that cross talk between adjacent pixels is not a problem in the display. The unrotated pixels on the right side are due to flakes sticking to the ITO surface.

Fig 6.5 demonstrates the change in reflectivity that can easily be seen with the naked eye. The entire array 8 x 32 array of 1270 x 423 µm pixels is addressed with a 2.5 V_{p-p} 100 Hz AC signal in order to turn 'off' all of the pixels. The before and after pictures demonstrate an easily visibly change in brightness between the on and off states. The remaining unrotated pixels shown in the bottom picture can be attributed to either poor contact to the aluminum pads or defective pixels.

VI. Current Problems and Future Work

A. Active Matrix Issues

One of the attractions to PCLC technology is its ability to produce high contrast images of any color without polarizers or color filters. Unfortunately when the flakes are above a reflective substrate, like aluminum, it is difficult to differentiate between the reflectance of the PCLC flakes versus the light reflected by the substrate. This problem is clearly illustrated in the difference in color and brightness between the top and bottom images in Fig 6.1, which shows a 64 x 64 device both with and without the polarizer. Some grain can be seen without the polarizer, however the contrast is so low that it is practically negligible. The aluminum reflects nearly the entire spectrum of incident light, defeating the purpose of having a selectively reflective material above it. This known fault of the first generation technology is remedied by adding a circular polarizer to the display, which significantly increases the display contrast.

Future iterations of the active matrix need to substitute the aluminum for an alternate non-reflective conductive material. This would allow the device to operate without a polarizer and significantly reduce the price and complexity of any commercial application. Possible materials include moving to a completely transparent device and using ITO in substitute for the aluminum. Alternatively, a dark or black metal such as Titanium Nitride could be used. Other materials should be investigated with the primary qualifications being low resistance, low reflectance, and patternability.

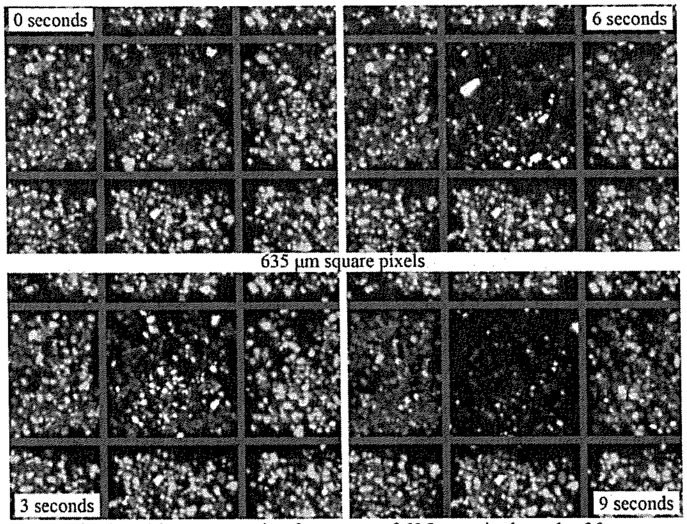

Fig 6.3 This sequence is of an array of 635 μm pixels under 30x magnification, as seen through a polarizer. The blue lines are added to show where the SU8 boundaries are present between pixels. The series of images demonstrates the high contrast capability of the display when it has a high density of PCLC flakes.

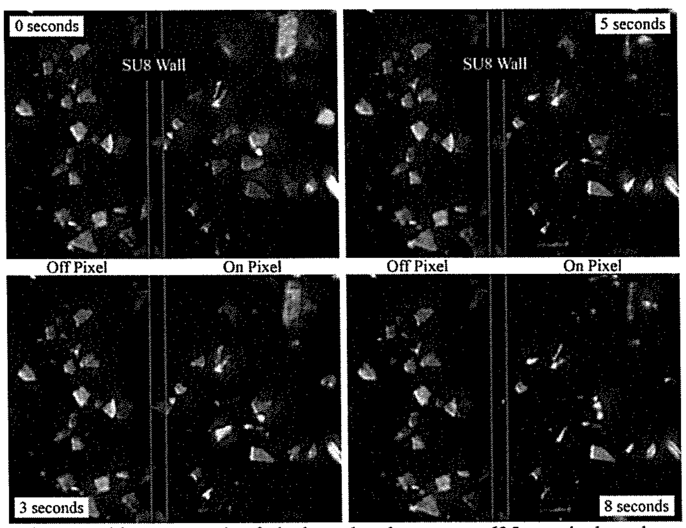

Fig. 6.4 This sequence is of the boundary between to 635 μm pixels under 100x magnification, as seen through a polarizer. The low density of PCLC flakes enables viewing of individual flake rotate. The pictures shows that strong isolation between pixels is achieved. Long rotation time of 8s can be reduced using higher drive voltages than the applied 2.5 V_{pp}.

Other problems with active matrix display to address include: routing, isolation, scalability and both response and relaxation times. Routing and isolation of signals is the next most significant problem in the displays. Routing in diffused silicon should be avoided and a multi-level metal system needs to be incorporate into future iterations.

B. PCLC Issues

A combination of PCLC specific issues need to be addressed. The most important problem is the inability of the display to reorient themselves back to their reflecting state without waiting for gravity to naturally relax them. This is most limiting aspect of the technology and is of primary concern. Several solutions are being researched including the development of a unique waveform to 'shock' the flakes back into their horizontal position. Secondly, a novel device structure could be used to apply a horizontal field to a pixel.

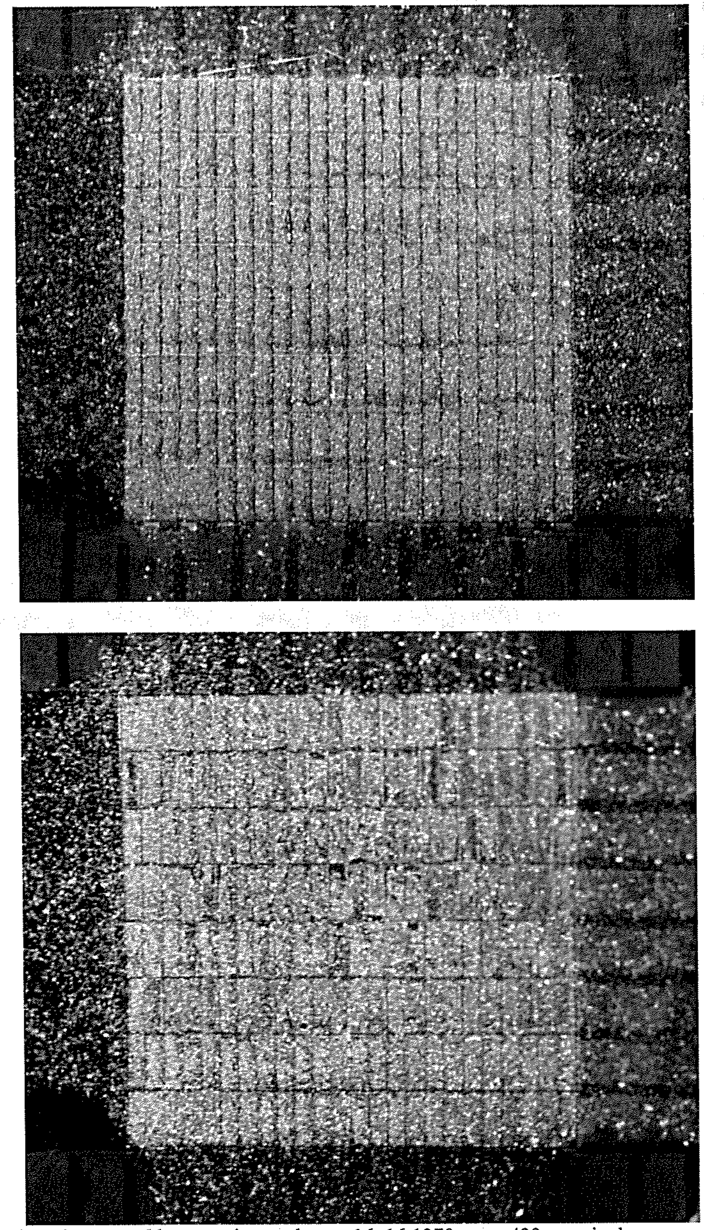

Fig 6.5 The top and bottom picture show a 16x16 1270 μm x 423 μm pixel display before and after being addressed. All of the pins where biased with a 3.5 V_{pp} 100 Hz signal. The bottom display shows that the majority of pixels have turned off. The remaining unrotated pixels may be due to defects in the active matrix and or bad contact to the aluminum pads.

Secondly, the response time and variation of the displays can also be significantly enhanced (<100 ms) using LLE's unique shaped flake technology. This allows for uniform PCLC flakes to be used that have identical response and relaxation times. Also, using layered shaped flakes which are made of two materials that reflect left and right handed polarization states respectively will allow for displays with near 100% reflectance at the designed wavelength.

VII. Conclusion

A custom active matrix back pane was design, fabricated, and packaged for use with PCLC flake display

technology. The fabricated displays demonstrated the ability to individually address pixels inside of an array.

Future iterations of the technology need to incorporate non reflective materials and advanced PCLC technology such as shaped and layered flakes. With these changes PCLC flake displays represent a real and viable technology for low power and low cost display applications.

VIII. Acknowledgements

RIT: Dr. Sean Rommel, Dr. Lynn Fuller, Tom Grimsley, Adam Randall, Stuart Sieg, SMFL Staff

LLE: Gerald Cox, Ken Marshall, Dr. Steven Jacobs, Dr. Tanya Kosc, Catherine Fromen

IX. References

[1] J. D. A. B. Comiskey, H. Yoshizawa, and J. Jacobson, "Electrophoretic ink for all-printed reflective electronic displays," *Nature,* pp. 253–255, 1998.

[2] E. A. R. N. K. Sheridon, J. C. Mikkelsen, D. Tsuda, J. C., K. A. O. Crowley, M. E. Howard, M. A. Rodkin, R. Swidler,, and a. R. Sprague, "The Gyricon rotating ball display," *Journal of the Society of Information Displays,* pp. 141-144, 1999.

[3] T. Z. Kosc, K. L. Marshall, S. D. Jacobs, J. C. Lambropoulos, and S. M. Faris, "Electric-field-induced motion of polymer cholesteric liquid-crystal flakes in a moderately conductive fluid," *Applied Optics,* vol. 41, pp. 5362-5366, Sep 2002.

[4] A. T. Petkoska, "Polymer Cholesteric Liquid Crystal Flakes in Host Fluids," in *Institute of Optics*. vol. Ph.D. Rochester: University of Rochester, 2007, p. 303.

[5] T. Z. Kosc, K. L. Marshall, S. D. Jacobs, and J. C. Lambropoulos, "Polymer cholesteric liquid-crystal flake reorientation in an alternating-current electric field," *Journal of Applied Physics,* vol. 98, Jul 2005.

[6] T. B. JOnes, *Electromechanics of Particles*. New York: Cambridge University Press, 1995.