Flexible Dispay Technology for the Objective Force

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ABSTRACT

The Army has initiated a flexible display research program. This program is part of the Army's strategy to create technologies that will enable revolutionary designs and transformational weapons systems for the Objective Force. The ARL flexible display program is more general than just for the dismounted soldier-it will also have implications for air and vehicular crews, and for the other services, even though it is not a DoD tri-service program per se. "Flexible" is defined in the program as displays that operate under conditions from conformal applications, limited flexing, to roll-able displays for compact storage. The Army program will include display manufacturing concepts that enable roll-to-roll processes reduce cost, to tap a strong U.S. domestic industrial strength, and, eventually, to enable fabrication of very large sizes. There is commercial interest in flexible displays for applications ranging from wearable electronics for road-warriors and gamers to large screen 71-in. 1920x1200 color pixel consumer high definition television sets for walls. Industry willingness to cost share will be a key criterion in identifying investment opportunities that are necessary and timely from among all that may be envisioned. Some anticipated military applications and a roadmap are presented that identify the technology barriers at the materials, device and manufacturing levels to the creation of flexible display technology.

Keywords: Flexible, organic light emitting devices, polymer, small molecule, reflective, thin film transistors, and electrophoretics.

1. INTRODUCTION

The Army is undergoing a transformation that will reduce the weight, increase the lethality, improve the situational awareness, and enhance the survivability of the warrior. The transformation is an evolution from the Future Combat System (FCS) through the Objective Force (OF). The Objective Force Warrior (OFW) is one of the central sub-systems for OF system of systems. To meet the challenges for the transformation, the data from the supporting sub-systems must be conveyed to the warrior through a variety of displays. The Army is currently investing in the development of flexible displays for the Army Transformation through the Flexible Display Initiative (FDI) in FY04-FY09. Flexible displays will offer improved ruggedness, reduced weight, and novel applications such as roll-up while maintaining the power efficiency of the display technologies under development. In this paper, we will review the Army Transformation and the application requirements that drive the display specifications. Some of the display technologies with attributes compatible with flexible substrates will be reviewed as well as the Army's Flexible Display Initiative (FDI).

2. THE ARMY TRANSFORMATION AND DISPLAYS

The Army Transformation evolves from several key blocks starting with the future combat systems (FCS) through the Objective Force. The OF is the Army's flagship Science and Technology initiative to develop and demonstrate revolutionary capabilities for the Army's Transformation. An integrated system of systems approach is being employed to support the Army transformation to a soldier-centric force. The OFW is a major pillar of the Objective Force strategy. The OF subsystems development are categorized by the five primary areas; lethality, survivability, sensors and communication, power, and mobility.

The correlation of these requirements to flexible displays is: LETHALITY: Improved information transfer to the soldier though higher bandwidth and resolution; SURVIVABILITY: Rugged, light-weight, reduced emissions; SENSORS and COMMUNICATIONS (C4isr): Ubiquitous displays at low cost; POWER: efficient, bistable; MOBILITY: light weight, foldable, roll-able.

The Army Transformation to a soldier-centric system requires unprecedented information to the individual from the supporting sub-systems. This information must be displayed to the soldier on a system that is rugged, lightweight, low power, and environmentally stable. The displays for the Army Transformation will have a variety of requirements in size and capability for the individual soldier and the vehicle applications. Displays on flexible substrates are an enabling technology for advanced performance in military systems. Conformal displays will be an enabling step toward fully flexible displays. Fig. 2 illustrates the road map from glass-based, ruggized military displays to fully flexible displays.

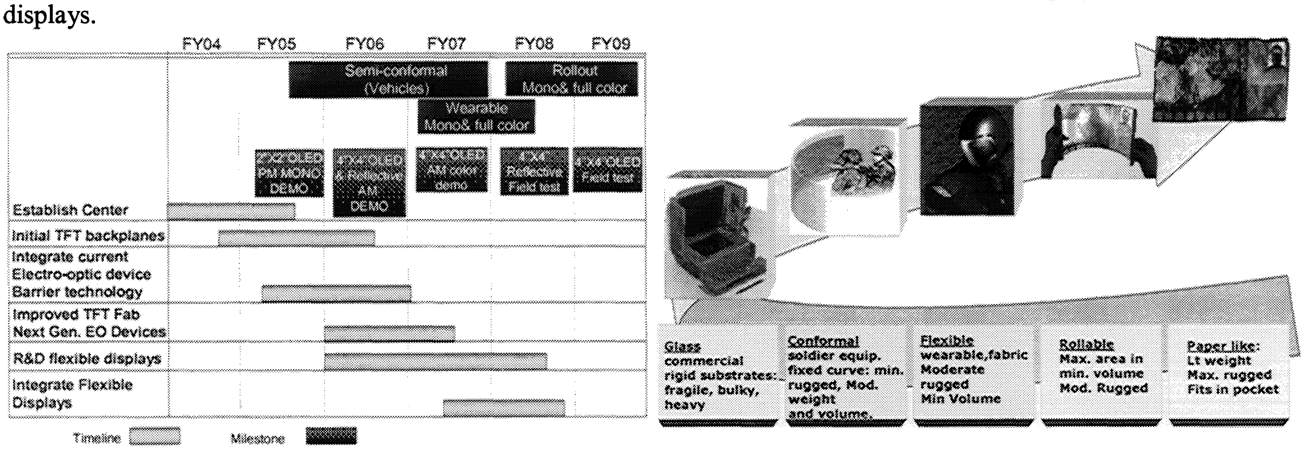

Fig 2 Flexible Display Initiative timeline and technology milestones based on a University lead center. Fig. 2b illustrates the definitions for the degrees of flexibility.

The requirements for military display performance remains a challenge compared to the current commercial performance, particularly in resolution, power efficiency and environmental ruggedness. These challenges must be met with conventional substrates in the near term and with flexible substrates for improved performance. The flexible attribute may enable applications where conventional substrates cannot meet the requirements.

3. DEFENSE ADVANCED RESEARCH PROJECTS AGENCY (DARPA) PROGRAMS

From 1989-1999, The DARPA display programs enabled the progress of a variety of display technologies. Some of the programs have technologies compatible with low-temperature processing and therefore flexible plastic substrates. In 1999, DARPA initiated a flexible display program with the specific aim to develop flexible, plastic substrate-based displays for the war-fighter. The Flexible Display programs funded by DARPA included; the electro-optic materials and devices for passive and active matrix displays (i.e. organic based light emitting devices (OLEDs), electronic ink and other reflective display approaches), low temperature processing for flexible backplane electronics, and substrate and environmental barrier technologies.

For Emissive displays, organic based light emitting devices have demonstrated full color, high efficiency and room temperature processing compatible with plastic substrates. The substrate must have significant moisture barriers. Since the first announcement of efficient electroluminescence (EL) from a bi-layer organic light emitting diode, significant research and development has lead to commercially viable technologies for glass-based flat panel displays. [1] In 1990, EL was reported in polymer systems based on thermally converted poly(1,4-phenylene-vinylene (PPV). [2] Later EL was observed in polymer devices based on soluble substituted poly(1,4-phenylene-vinylene). [3] For both materials systems, the organic layer(s) and metal cathodes are deposited at room temperature, which has led to the possibility of developing full color displays on flexible, plastic substrates that are lightweight, conformal towards roll-able, and possibly roll-to-roll processing. OLEDs generate light through the electrical injection of electrons and holes that recombine at a neutral excited fluorescent or phosphorescent molecule.

The first commercial insertion for OLEDs by Pioneer was small passive matrix displays for automotive stereo displays and cellular phones. [4] These small display formats have additional applications that could include; hand-held electronics such as, global position systems, PDAs, cellular phones with internet access, and others. For all of these applications, the display sizes are suitable for passive matrix driven displays. Fig. 3 is an illustration of a typical passive matrix OLED display structure. Here, the indium tin oxide anodes (ITO) are patterned in stripes, followed by a cathode separator. The organic materials, small molecules or polymers, are deposited over the substrate followed by the metal cathode patterned by the cathode separators. The pixel is defined as the intersection between the cathode and anode stripes. Further, this design relies on the diode nature of the organic device as the driving schemes require that several organic devices be operated in reverse bias. Thus, the reverse bias leakage current in the device must be kept low for optimum display operation. Further details of passive matrix designs can be seen in Ref. 5 and are beyond the scope of this article.

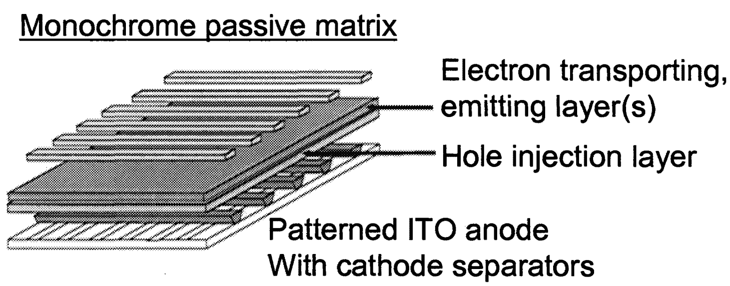

Fig. 3 is a passive matrix, monochrome OLED based display.

Liquid crystal technologies dominate the reflective and transflective display markets. In addition to traditional liquid crystal approaches, reflective flexible displays have been demonstrated from two technologies, polymer dispersed liquid crystal [6] and micro-encapsulated electrophoretic spheres (electronic ink) [7]. Electronic ink is a proprietary material that is composed of many microcapsulated spheres approximately 100μm in diameter.[7] The spheres contain positively charged white particles and negatively charged black particles. When a positive charge is applied to a top transparent electrode, the black particles move to transparent electrode and white particles to the back, which gives a black appearing microcapsule. A white microcapsule is achieved by the reverse bias. Further, once the black or white particles have been moved under an applied bias, the voltage can be removed and the microcapsule remains meta-stable in the state. This property can be used to dramatically reduce the power consumption of displays for certain applications.

As the display size increases above approximately 3 inches and 200 lines, the resistive and capacitive loses in the ITO cathodes become unacceptable. The address time per row is inversely proportional to the number of lines so the duty cycles become small. Thus, large displays (greater than 3 inches) with high resolution (more than 200 lines) require active matrix drivers, where one or more transistors drive each pixel. The development of active matrix backplane electronics with processing conditions compatible with a flexible substrate remains a significant challenge for the overall goal of producing flexible displays. There have been a variety of approaches taken develop flexible electronics. A typical active matrix cross section is illustrated in Fig. 4.

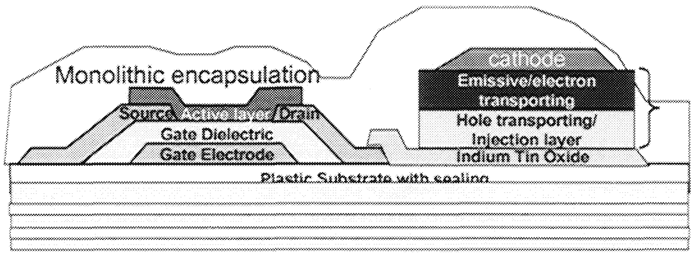

Fig. 4 is a typical active matrix cross-section.

FlexIC, Inc. has been developing ultra-low temperature poly-Si thin film transistors (TFTs). The approach is to first deposit amorphous Si at room temperature and re-crystallizing the Si with a laser. [8] This "ultra-low temperature poly-silicon (ULTPS)" TFT process was developed by the founders of FlexICs and offers semiconductor circuitry with a maximum processing temperature of 100°C. This approach utilizes a top gate structure, where the active Si layer is deposited first followed by the source and drain, gate dielectric and then the gate electrode and capping layer (inverted to the structure shown in Fig. 4). The FlexICs process offers NMOS devices with electron mobilities of 250 cm^2/V-sec and threshold voltages of 5 Volts, while PMOS process offers hole mobilities of 200 cm^2/V-sec and threshold voltages of –6V. Both processes have a 4 μm design rule, which leads to small pixels for higher resolution displays. The high mobilities are important as this allows the row and column drive circuitry to be integrated directly on the plastic substrate. When the mobilities for the TFTs are low then the driver circuitry required is single-crystal Si and must be mounted outside the display and connected to the row and columns through fine lead pitch interconnects. Fig. 5 shows a flexible substrate with the circuitry.

Prof. Tom Jackson's group at Pennsylvania State University is developing TFT's based on organic molecules. Here, the active layer shown in Fig. 4 is a small molecule, pentacene deposited at moderate base pressures with a substrate temperature from room temperature to 90°C and therefore can be grown on plastic substrates. This molecule naturally forms large crystallites on amorphous substrates. The TFT's are p-channel with mobilities as high as 3 cm^2/V-sec.[9] These values are comparable to amorphous Si. In addition to OLEDs, the Jackson group and David Sarnoff Research Lab have demonstrated flexible liquid crystal reflective displays utilizing organic TFTs as the drivers. [10]

In addition to these three approaches, many groups are actively pursuing amorphous Si (a-Si:H) based TFT's for the OLED driver electronics. Currently, the process temperatures for hydrogenated a-Si are 200-300°C. However, there are some efforts to lower this temperature sufficiently to prepare a-Si on plastic substrates. Typically, a-Si offers electron mobilities of approximately 1-5 cm^2/V-sec. As the efficiency of OLED devices improves, the requirements on the driver electronic mobilities decrease. Display designs based on amorphous Si TFTs will require row and column driver chips to be mounted and connected to the display.

Fig. 5 illustrates an active matrix, full color OLED-based display. Similarly, Fig. 6 illustrates an electrophoretic based display utilizing an active matrix driver scheme.

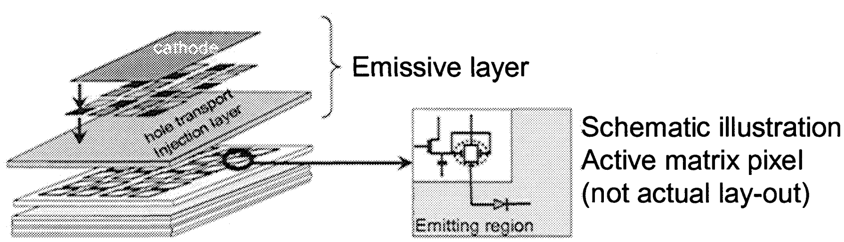

Fig. 5 is a typical active matrix organic display design.

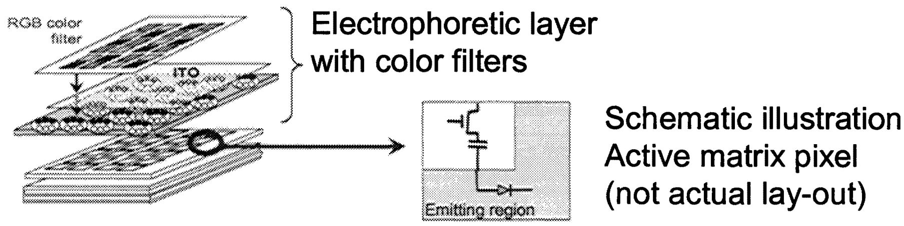

Fig. 6 is an illustration of a typical electrophoretic display.

For most display technologies, the materials are sensitive to long term exposure to air and water, where some technologies have significantly more severe requirements as compared to others. For glass substrates, this sensitivity requires a low permeability glue or seal between to glass plates or glass and metal. In general, water absorbing materials are included in the packaging.[4] For plastic substrates and displays intended for flexible applications the H_2O permeability through the substrate is a significant challenge. Vitex Systems has developed a Barix coating composed of alternating layers of polymers and ceramic thin films on a plastic substrate, similar to those illustrated in Fig. 5 and 6. The multi-layer structure offers substantial improvement in the H_2O permeability as compared to plastic substrates without the barrier layers and illustrated in the figures above.

4. ARMY'S FLEXIBLE DISPLAY INITIATIVE

The prospect for flexible displays has generated much interest in the commercial and military community. Fig. 7 highlights the timeline for flexible display development with a few of the key milestones.

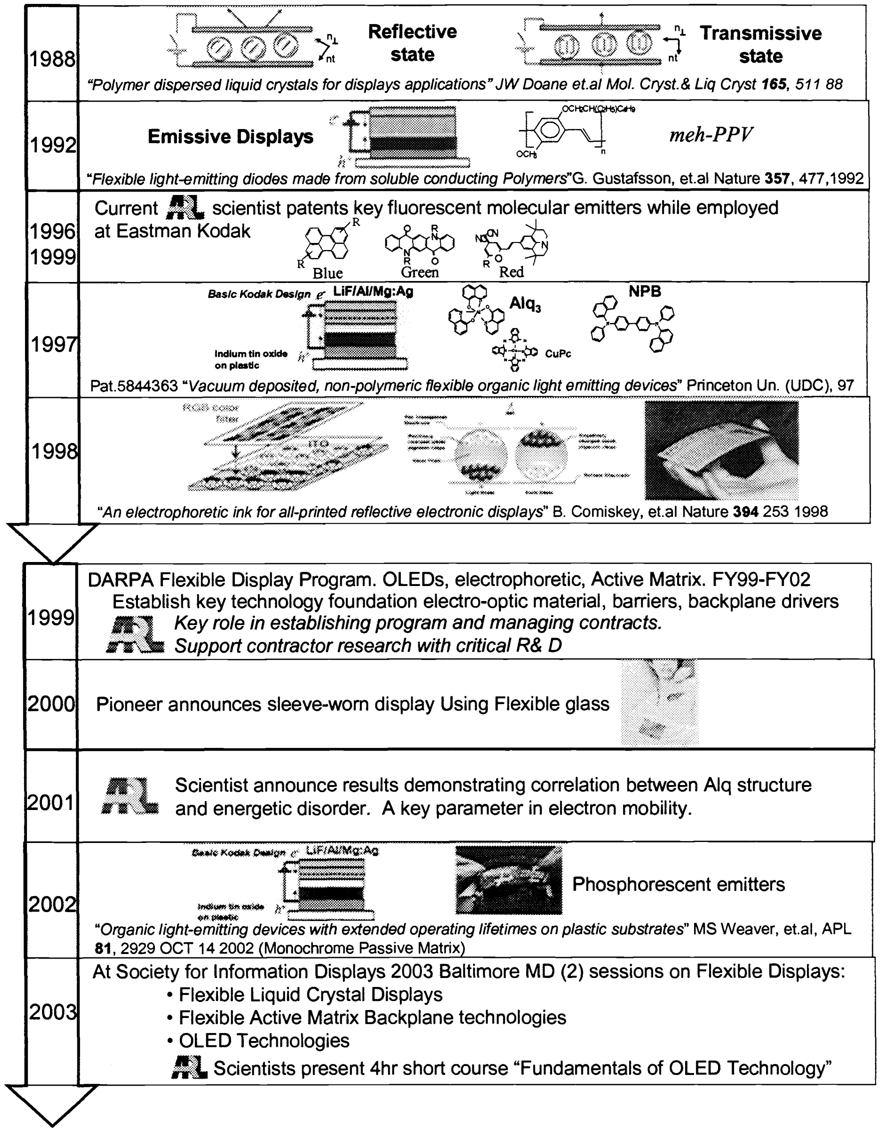

Fig. 7 is a timeline summary for Flexible Display Milestones

The US Army is responding to the needs for the Army Transformation of information displays by sponsoring a Flexible Display Initiative (FDI) from FY04-FY09. The Army FDI is aimed at the development of emissive and reflective flat panel displays on flexible substrates. For most military and some commercial applications, glass substrates require additional ruggedization to meet the environmental challenges. A flexible plastic or metal substrate may reduce these ruggization requirements. Flexible displays have the advantage of lightweight, rugged, and low power, the key requirements for the Objective Force Warrior (OFW) as well as other Army weapon platform applications. The program will identify a range of flexibility from conformal to rollable when not in use for a variety of military and commercial applications as illustrated in Fig. 2.

The FDI is intended to address the critical challenges for the development of flexible displays in the following program elements; electro-optic materials, backplane electronics, substrates and barriers, and manufacturing and integration. The FDI elements will build upon the previous DOD investments as well as the significant commercial market, as illustrated by the base of the pyramid. In addition, the Army intends to coordinate the program with other ongoing research and development activities that include the DOE lighting initiative, other DARPA programs, the NIST ATP program for flexible electronics. The goal of the FDI is the establishment of a facility or capability that enables the production of the flexible displays in a limited quantity.

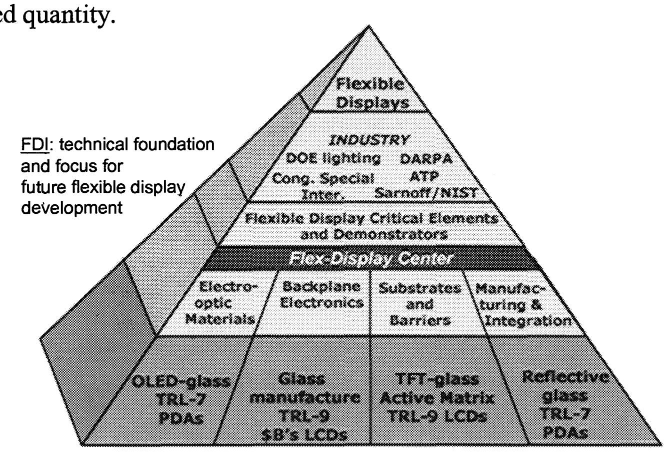

Fig. 8 is a pyramid approach for the Army's Flexible Display Initiative.

Fig. 8 summarizes the four critical elements for the FDI. Under each element is listed a few key challenges.

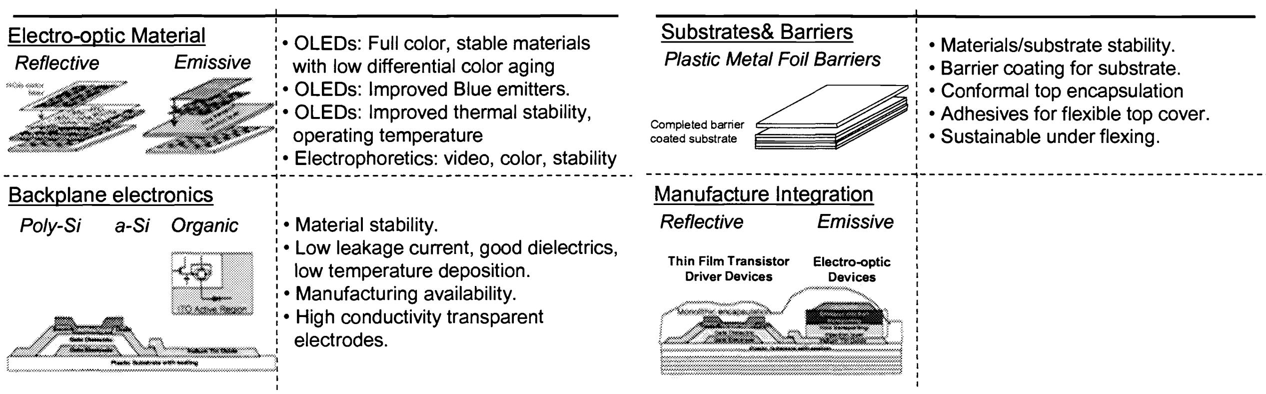

Fig. 9 is the four elements for the Flexible Display Initiative and the critical challenges for each element.

5. CONCLUSIONS

The goal for the Army's Flexible Display Initiative is the development and demonstration of flexible displays for the Army Transformation. The flexible display development will address the critical challenges for the development of emissive and reflective display technologies. These challenges are divided into four elements, electro-optic materials, backplane electronics, substrates and barriers, and manufacturing and integration. The FDI will address these critical challenges in focused, integrated approach to gain manufacturing capabilities for flexible displays. The flexible display demonstrators will be evaluated in the Army Transformation programs that include FCS, OF, and OFW.

REFERENCES

1. C.W. Tang, S.A. Van Slyke, "Organic Electroluminescent Diodes", *Appl. Phys. Lett.*, **51**, pp. 913-915, (1987).
2. J.H. Burroughes, D.D.C. Bradley, A.R. Brown, R.N. Marks, K. Mackay, R.H. Friend, P.L. Burns, A.B. Holmes, "Light emitting diodes based on conjugated polymers", *Nature*, **347**, pp.539-541, (1990).
3. G. Gustafsson, Y. Cao, G.M. Treacy, F. Klavetter, N. Colaneri, A.J. Heeger, "Flexible Light-emitting diodes made from soluble conducting polymers", *Nature*, **357** 477-480, (1992).
4. T. Tohma "Development of Organic EL displays using small molecule material", *Proc. Of the the 10th international workshop on inorganic and organic electroluminescence Hamamatsu Japan* pp.9, Dec. 4-7, (2000).

5. EW Forsythe "Operation of Organic Light Emitting Devices", *SID Short Course M-5 Boston MA*, , May 20, (02).
6. JW Doane et.al, "Polymer dispersed liquid crystals for displays applications" Mol. Cryst. and Liquid Crystals **165**, 511 1988
7. B. Comiskey, et.al "An electrophoretic ink for all-printed reflective electronic displays" Nature **394** 253 1998
8. P.M. Smith, P.G. Carey, T.W. Sigmon, "Excimer laser crystallization and doping of silicon films on plastic substrates", *Appl. Phys. Lett.*, **70**, pp. 342-344, (1997).
9. D.J. Gundlach, Y.Y. Lin, T.N. Jackson, S.F. Nelson, D.G. Schlom, "Pentacene organic thin-film transistors - Molecular ordering and mobility", *IEEE Elect. Dev. Lett.* **18**, pp. 87-89, (1997).
10. C. D. Sheraw, L. Zhou, J.R. Huang, D. J. Gundlach, M. G. Kane, I. G. Hill, M. S. Hammond, J. Campi, B. K. Greening, J. Francl, J. West, and T. N. Jackson, "Organic Thin-Film Transistor-Driven Polymer-Dispersed Liquid Crystal Displays on Flexible Polymeric Substrates" , *Appl. Phys. Lett,* **80**, pp. 1088-1090, (2002).