SPIE Meeting on Cockpit Displays IV: Flat Panel Displays for Defense Applications
Orlando, FL, April 21, 1997

Device technology for lightweight panoramic displays

S.J. Fonash[a], O. Awadelkarim[a], J.L. Crowley[b], T.N. Jackson[a], A. Kahn[c], J.C. Sturm[c], and S. Wagner[c]

[a]Pennsylvania State University, University Park, PA 16802, [b]C&C Technologies, Dayton, NV 89403,
[c]Princeton University, Princeton, NJ 08544

ABSTRACT

Active matrix displays that are lightweight, rugged and bendable are a key DoD need for applications ranging from panoramic displays for aircraft cockpits to foldable maps. To achieve such displays compatable substrates, TFT backplanes, and light valve/ light emissive materials systems must be developed. Advances toward this goal achieved in the joint Penn State/Princeton Display Program are discussed.

1. INTRODUCTION

Lightweight, rugged, bendable active matrix displays are needed for a range of applications from breastpocket, foldable maps to large, multifunction panoramic cockpit displays. To achieve such displays a variety of materials must be integrated into a robust system. This system must include the substrate material, the TFT backplane materials, and the light valve/light emissive materials. A key driver is the substrate choice which dictates whether emissive technologies, backlighted LC, or reflective LC technologies can be used. This choice then dicates whether the backplane pixel control is current based or voltage based. In this report we discuss the joint Penn State/Princeton display research program assessment of the various possible materials systems, and our results in working toward reliable and lightweight, bendable displays.

2. BENDABLE DISPLAYS: SUBSTRATE CHOICES AND CONSEQUENCES

As seen in Table I, there are a number of substrate choices for lightweight, bendable displays but each imposes varying degrees of constraints on the overall materials system. In general, plastics are very attractive due to their mechanical properties and lightweight. Clear plastics allow the use of backlit LC displays but currently available materials demand low processing temperatures (<150°C), in general require a diffusion/solvent barrier and a scratch-resistant coating [1]. Opaque plastics require top emissive or reflective LC technologies. However, some opaque plastics can withstand somewhat higher processing temperatures; in fact, an empirical correlation exists between glass transition temperature and opacity[2]. Opaque plastics need diffusion/solvent barriers and scratch-resistant coatings. Metal foils are again limited to top emissive or reflective LC technologies. Metal foils need to be polished or, when used in an as-rolled condition, they must be planarized[3]. The planarization layer may be combined with, or may be separate from the electrically insulating layer. Metal foils open the door to a broad range of processing temperatures, and experience gathered to date shows that the fabrication processes developed for glass substrates can be transerred easily to stainless steel foil substrates. Metals offer mechanical strength and the substrate can function as a ground plane. Glass foils could be used by themselves or bonded in a last step to plastics. This substrate choice would allow the use of processing temperatures of up to 600°C and may avoid the need for diffusion barriers and hard coatings inherent to plastics. Obviously, both emissive or backlit LC approaches could be used. Glass foils also have the advantage of allowing the transfer of display technology developed for low temperature sheet glass.

Table I. Substrate choice is the driver in *lightweight, rugged, flexible, rollable, foldable, low-cost displays.* Some of the decisions forced by the substrate choice are shown.

Substrate Choice	**Process Temperature**	**Encapsulant/ Diffusion barrier**	**Planarization/ Hard coating**	**Emissive Technology**	**Light Valve Technology**
Clear plastic	Limited to <150°C	Probably needed	Probably needed	May be used	Backlighting may be used
Opaque plastic	Limited to <200°C	Probably needed	Probably needed	Top emission only	Reflective mode
Metal foils	Broad range	May be needed	Probably needed	Top emission only	Reflective mode
Glass foils	Limited to <600°C	May not be needed	Not needed	May be used	Backlighting may be used

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 10/10/2016 Terms of Use: http://spiedigitallibrary.org/ss/termsofuse.aspx

Because of their flexibility and lightweight, plastic substrates appear very attractive. However, as seen from Table I, the use of plastic substrates imposes the most severe conditions on backplane and emitter processing. The consequences are noted explicitly in Table II. As seen, low temperature semiconductor, interlayer and gate dielectric, and interconnect deposition technologies must be developed for the backplane. In addition low temperature planarization and encapsulation processes must be developed.

Table II. Process requirements and level of innovation needed for plastic substrates.

Function	Requirement	Level of innovation
Semiconductor	Very low temperature deposition Stress compatibility	High
Gate dielectric	Very low temperature deposition Stress compatibility	High
Interconnects	Very low temperature deposition Stress compatibility	Low
Interlayer Dielectric	Very low temperature deposition, spin-on Stress compatibility	Intermediate
Diffusion barrier	Very low temperature process	Intermediate
Hard coating	Very low temperature process Stress compatibility	Low

3. MATERIALS SYSTEMS CANDIDATES

Table I can be used to identify materials systems that are potential candidates for bendable displays. For example, if opaque plastic or metal foils are used, reflective LC, or the emissive EL or LED technologies are required. The light emissive approaches may necessitate poly Si TFTs for high drive currents; however, it is becoming apparent that organic or a-Si TFTs may prove adequate and reliable at the required current levels. In the case of opaque plastic substrates all the processing must follow Table II. If glass foils are used, then light valve LC and a-Si backplane TFT technologies developed for low temperature sheet glass may be applied. If transparent plastics are used, then again light valve technology may be used with a-Si TFTs; however, the constraints of Table II have to be followed. Thus the semiconductor and dielectric deposition temperatures currently used for a-Si-based AMLCDs have to be lowered. If poly-Si or organic TFT backplane approaches are used with transparent plastics, Table II again must be followed.

As a result of these various constraints we have chosen several carefully selected materials systems for evaluation as lightweight, panoramic display candidates. To take advantage of the broad range of technology options available to us, the systems we have chosen use the extremes in substrate materials: plastics and metal foils. Thus the specific systems we are exploring are the (1) Plastic-organic TFT-OLED or LC, (2) Metal foil-organic TFT-OLED, (3) Plastic-a-Si TFT-OLED or LC, (4) Metal foil-a-Si TFT-OLED, (5) Plastic-poly-Si TFT-OLED or LC, and Metal foil-poly-Si TFT-OLED systems.

4. SELECTED RESULTS OF THE PENN STATE - PRINCETON JOINT RESEARCH AND DEVELOPMENT PROGRAM

A. Plastic or metal foil substrate - Organic TFT electronics - OLED emitter or LC light modulator

Since OLED and LC processing can be achieved near room temperatures, and organic TFT processing appears achieveable for temperatures < 200°C, a display materials system with these components and based on a plastic substrate seems possible. A summary of our results to-date for the organic semiconductor TFT that is the key to this low temperature approach is shown in Fig. 1. The organic semiconductor used in these TFTs is pentacene. As may be noted from the figure, mobilities > $1 cm^2/V\text{-}s$ and subthreshold swings ~ 1.6 V/decade have been attained. Threshold voltages ~ 0V have also been demonstrated. These preliminary, yet world-record, performance results have been attained using the basic configuration seen in Fig 2; i.e., test structures using a Si wafer gate and a thermally grown dielectric. As also seen in Fig. 2, a simple organic TFT inverter has been fabricated lithographically and demonstrated.

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 10/10/2016 Terms of Use: http://spiedigitallibrary.org/ss/termsofuse.aspx

Table III. Characteristics of amophous/poly-crystalline silicon films produced by ECR-PECVD

Sample No	17	20	19	18
Dep. temp (°C)	30	120	220	310
Photo-Sensitiviy (Ip/Id)	~10^4	1.6x10^3	2x10^3	5
Dark-conductivity (S/cm)	≤1x10^{-12}	?	~ 5.8x10^{-10}	~ 9.4x10^{-8}
XRD	amorphous	amorphous (crystalline?)	(220)/(111) crystallinity	(220)/(111) crystallinity
UV peak height (280 nm)	0.5 %	0.75%	1%	1%
After Anneal	2.5%	2.5%	1.5%	1.25%
Crystallinity(=UVPHBA/UVPHAA)	20%	30%	70%	80%
Reflectance at 200 nm	61%	68%	80%	79%
Tail Photo-Luminescence Ep	1.17 eV	1.12 eV	1.04 eV	0.93 eV
Eg (PL)	~1.90 eV	~1.88 eV	1.31 eV	1.19 eV
Raman peak (/cm)		after X-alize 519	516	519
R half wid (/cm)		7	16	16
Act. Energy(Ea) 50 - 80 °C	?	0.61 eV	0.66 eV	0.62 eV
Sensitivity to BOE	No	No	No	No
Thickness (A)	~3400	~3400	~3400	~3400

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 10/10/2016 Terms of Use: http://spiedigitallibrary.org/ss/termsofuse.aspx

B. Plastic or metal foil substrates - a-Si TFT - OLED emitter or LC modulator

We have already achieved the successful integration of a-Si TFT and OLED technologies on a flexible stainless steel foil substrate. The details of the structure used are seen in Fig. 3 and the integrated a-Si TFT / OLED in operation is seen in Fig. 4. It is important to note that the TFT is driving the OLED while the structure is being bent. Additional information on the robustness of these TFTs on stainless steel foils is seen in Fig. 5. The TFT characteristics did not change during or after the 150 hour bending stress application. They also did not changed when dropped 15m onto concrete. We estimate that ~ 10% of the pixel area will be required for the switching and the current control TFTs if made of a-Si. Therefore, the steel foil/a-Si TFT/OLED structure could provide the foundation for a very rugged display technology.

Fig. 6 shows that we have also made significant progress toward a three color, a-Si driven OLED display. Here we show results for the first 3-color, integrated OLEDs with 3 organics. All dry processing was used for patterning and etching to avoid damaging the organic LED materials.

C. Plastic or metal foil substrate - poly-Si TFT - OLED emitter or LC modulator

The emphasis here has been on lowering the processing thermal budget required for obtaining good quality poly-Si. Two approaches have been taken: solid phase crystallization (SPC) of a-Si precursor films using metal catalyzed crystallization and direct deposition of poly-Si using a high density plasma source. In the former case we have further developed our metal catalyzed SPC technique so that the catalyzing metal may be applied by spraying or dipping. Hence a vacuum deposition step for applying the catalyzing metal is no longer required. These non-vacuum metal treatments substantially lower the SPC thermal budget. For example, the SPC time at 600°C is lowered from 15 hours to a few minutes with this treatment as seen in Fig 7.

In the case of the high density plasma direct deposition of poly-Si, it can be seen from Table III that we are now able to use an electron cyclotron resonance (ECR) tool to deposit a high quality poly-Si film at temperatures ~200°C. Fig. 8 shows that we have been able to deposit good quality silicon nitride at temperatures as low as room temperature with this tool. We currently are developing oxynitrides for use with the poly-Si in the low temperature fabrication of poly-Si TFTs.

5. CONCLUSIONS

Using a teaming approach the Penn State/Princeton program has developed new approaches to the bendable, rugged and lightweight display technologies needed by the U.S. Armed Forces for a range of applications, from mass-produced portable devices to large, curved panoramic displays. We have produced organic TFTs at temperatures <200°C. These TFTs have attained the world record mobility for an organic TFT and attained low threshold voltage and subthreshold swing values. We have demonstrated a lithographically defined organic TFT inverter.In addition we have demonstrated the first integrated a-Si TFT/OLED, the first integrated a-Si TFT/OLED on an unbreakable substrate, and the first all-dry processed three color OLED. We have developed a new vacuum-less metal catalyzed crystallization process that substantially lowers the SPC thermal budget for crystallizing poly-Si from a-Si precursors. Further we have produced good quality ~200°C poly-Si deposited films and a good quality silicon nitride using ECR deposition allowing these materials to be used with plastic substrates.

ACKNOWLEDGEMENTS

This work was supported at Penn State and Princeton by DARPA grant #F33615-94-1-1464.

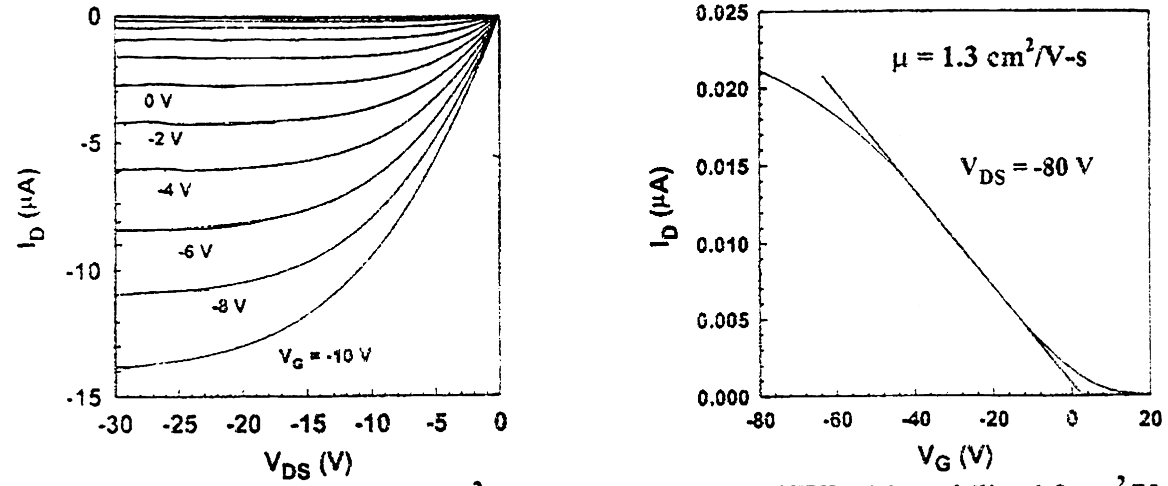
REFERENCES

1. S.M. Gates, “Prospects for Active Matrix Displays on Plastic,” *Mat. Res. Soc. Symp. Proc.* 467, to be published, 1997.

2. A. Stein et al., “Plastic LCD substrates that combine optical quality and high use temperature,” *SID 96 Applications Digest*, **A1.3**, pp.11-14, 1996.

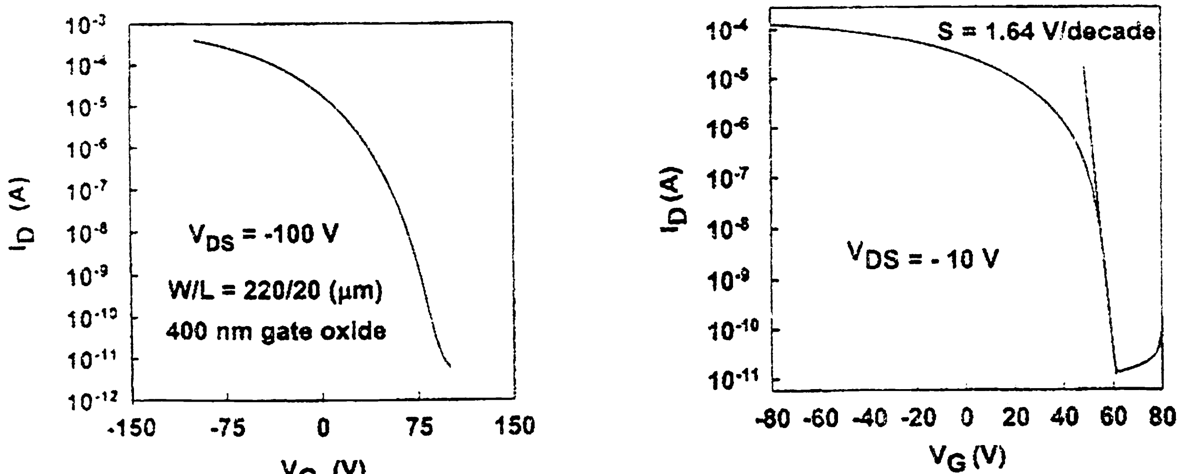
3. S.D. Theiss et al., “Flexible lightweight steel-foil substrates for a-Si:H thin-film transistors,” *Mat. Res. Soc. Symp. Proc.* **471**, to be published, 1997.

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 10/10/2016 Terms of Use: http://spiedigitallibrary.org/ss/termsofuse.aspx



Pentacene TFT with mobility 1.3 cm^2/V-s

Pentacene TFT with mobility 1.3 cm^2/V-s

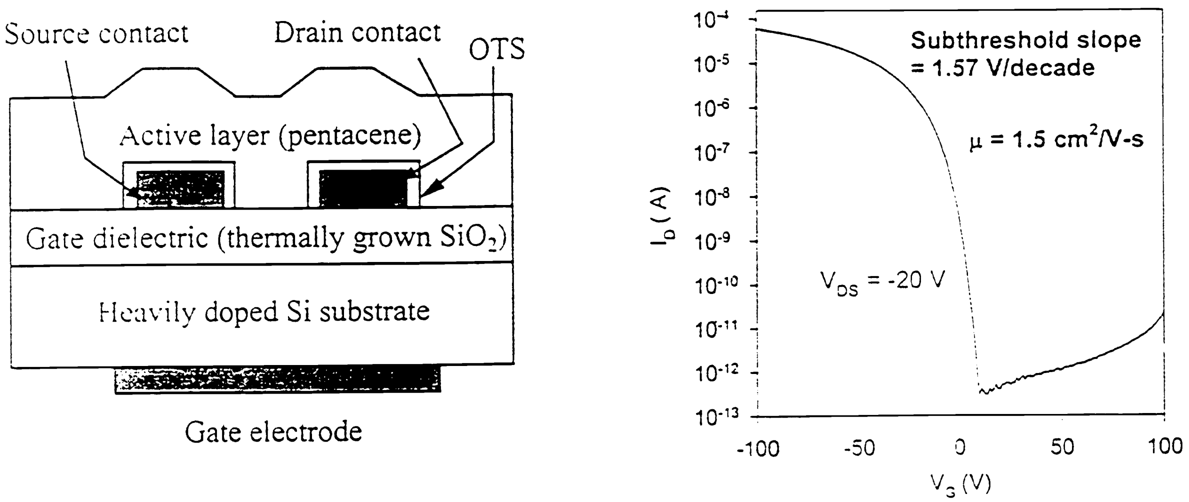


Pentacene TFT with Ion/Ioff > 10^8

Pentacene/Octadecyltrichlorodsilane TFT with 1.6 V/decade subthreshold slope

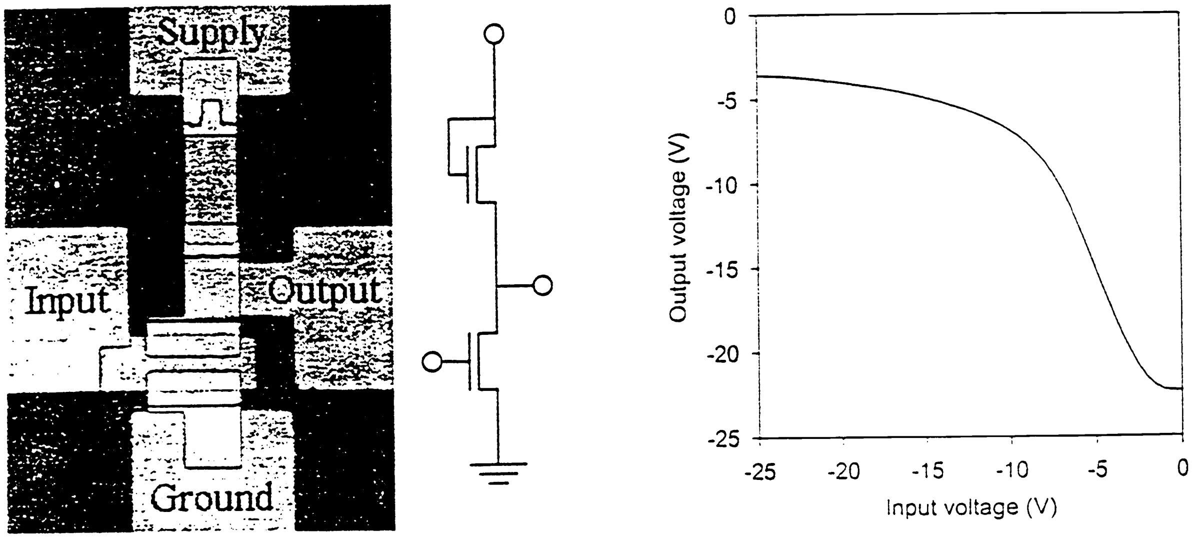
Fig. 1. Some pentacene TFT results. Data are not all from the same device.

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 10/10/2016 Terms of Use: http://spiedigitallibrary.org/ss/termsofuse.aspx



Photolithographically-defined pentacene TFT structure.

Log_{10} (I_D)-V_G characteristics for a lithographically-defined pentacene device.

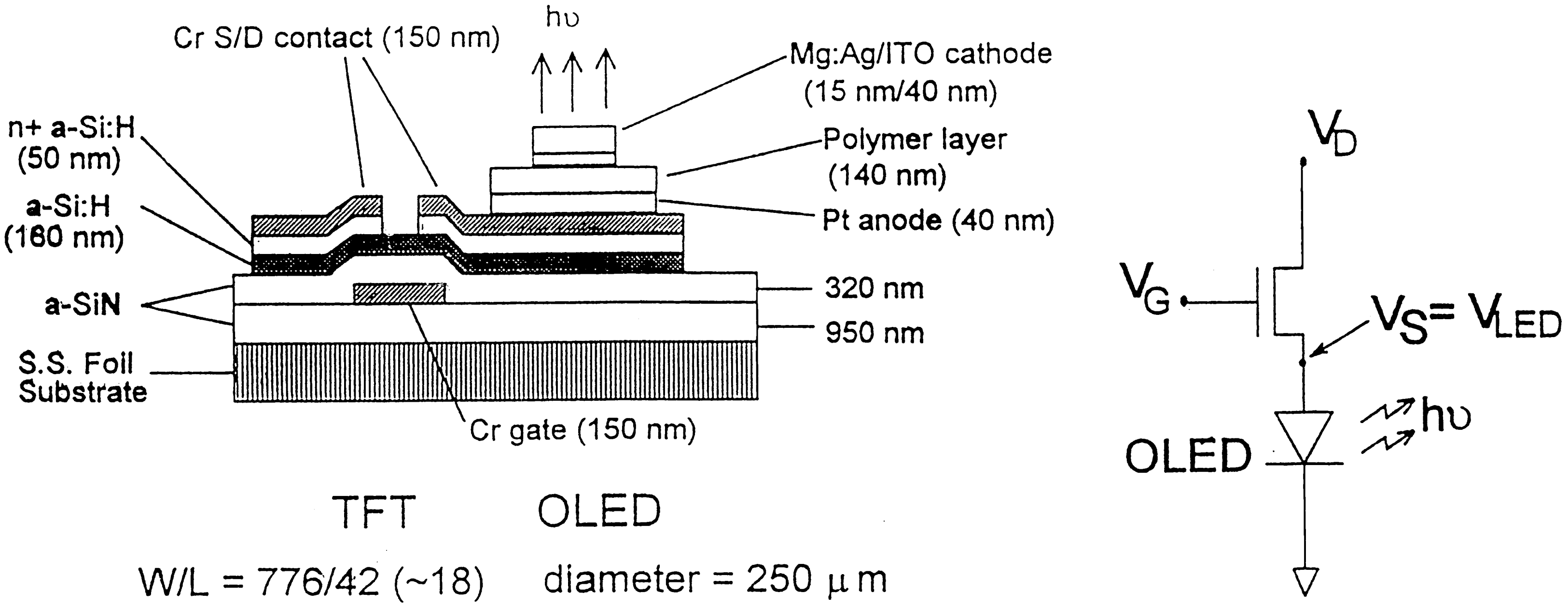


Inverter layout and schematic.

Inverter transfer characteristic.

Fig. 2. Pentacene organic TFT circuit demonstration.

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 10/10/2016 Terms of Use: http://spiedigitallibrary.org/ss/termsofuse.aspx



- TFT: Max. Process T = 310 °C
- OLED: Room T Process, top emitting

Fig. 3. Integration of a-Si TFT and OLED on flexible stainless steel foil.

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 10/10/2016 Terms of Use: http://spiedigitallibrary.org/ss/termsofuse.aspx

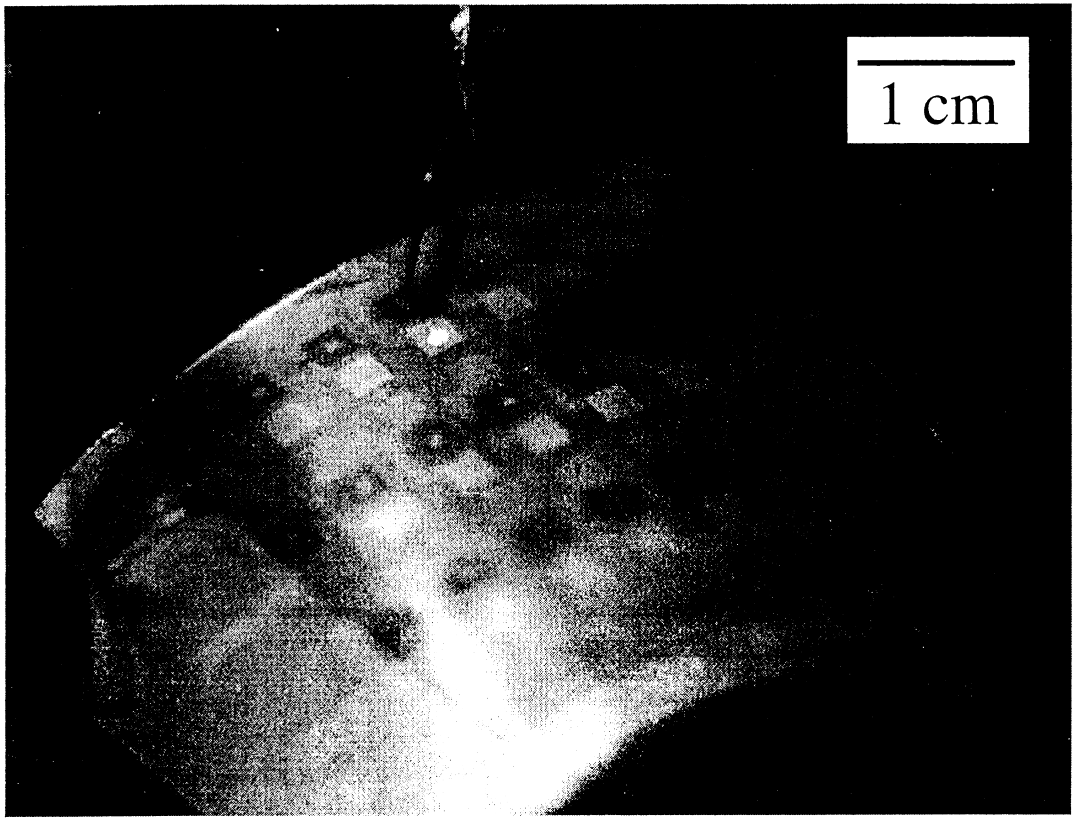
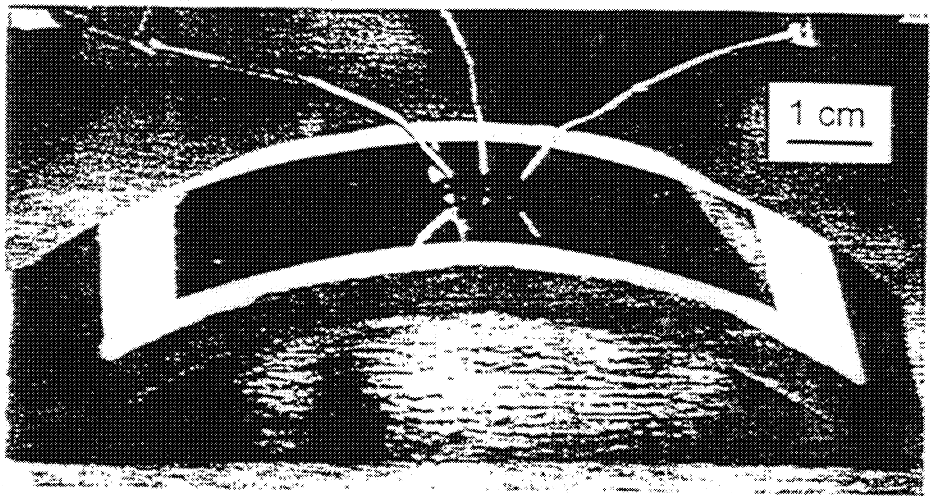


Fig. 4. TFT/OLED on a flexed steel foil.

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 10/10/2016 Terms of Use: http://spiedigitallibrary.org/ss/termsofuse.aspx

- Dropped 4 flr (~15m) onto concrete: no damage
- Bent to ROC=8.25cm: No change after 150 hours



Output Characteristics

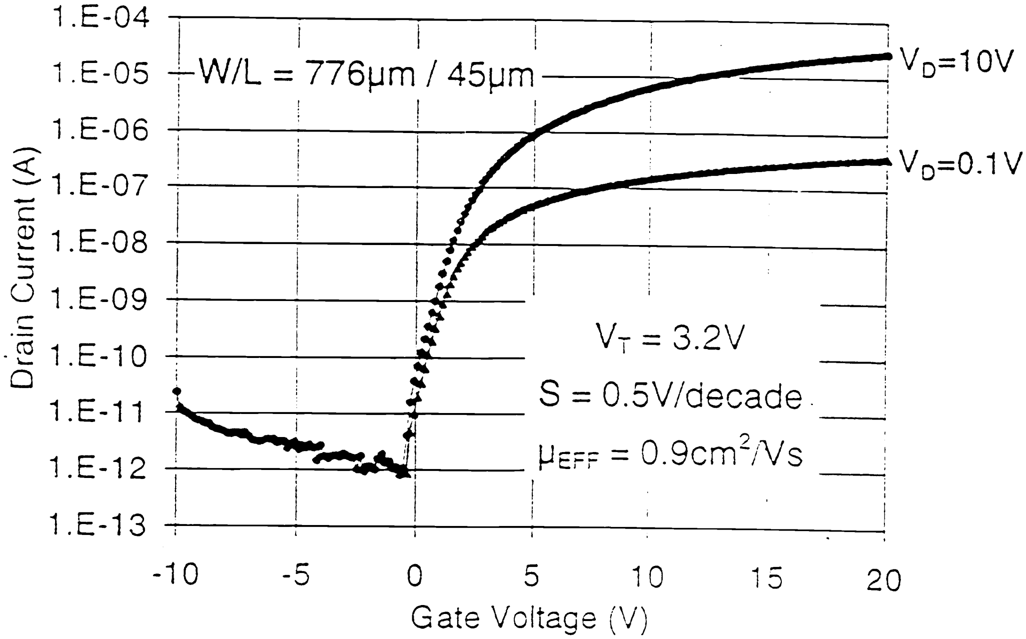


Fig. 5. TFTs under stress.

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 10/10/2016 Terms of Use: http://spiedigitallibrary.org/ss/termsofuse.aspx

	Color	ηext
ITO / PVK:Alq:nile red / Mg:Ag	Orange	0.7 %
ITO / PVK:PBD:coumarin 6 / Mg:Ag	Green	1.1 %
ITO / PVK:PBD:coumarin 47 / Mg:Ag	Blue	0.5 %

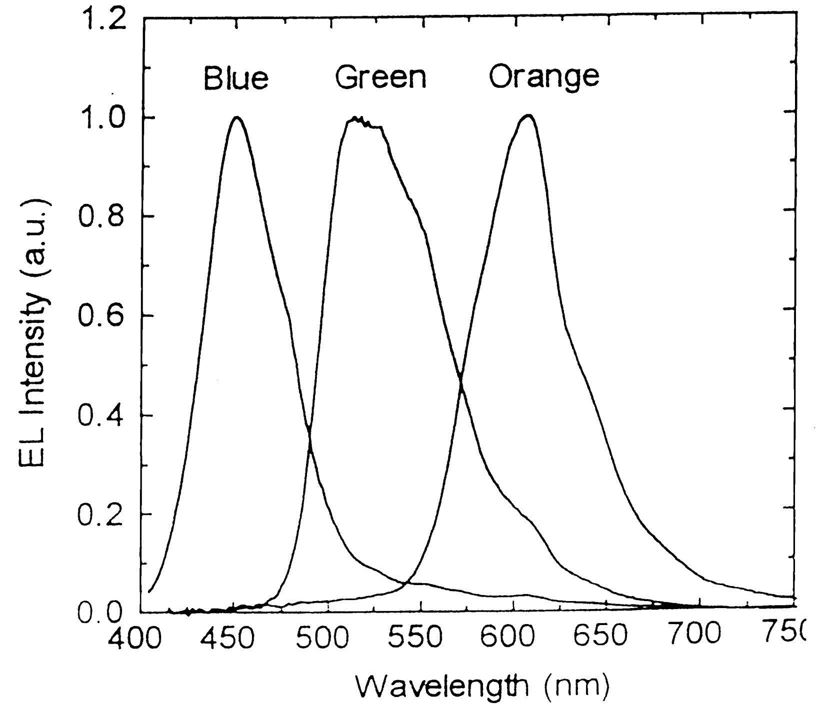


Fig.6. Summary of device performance.

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 10/10/2016 Terms of Use: http://spiedigitallibrary.org/ss/termsofuse.aspx

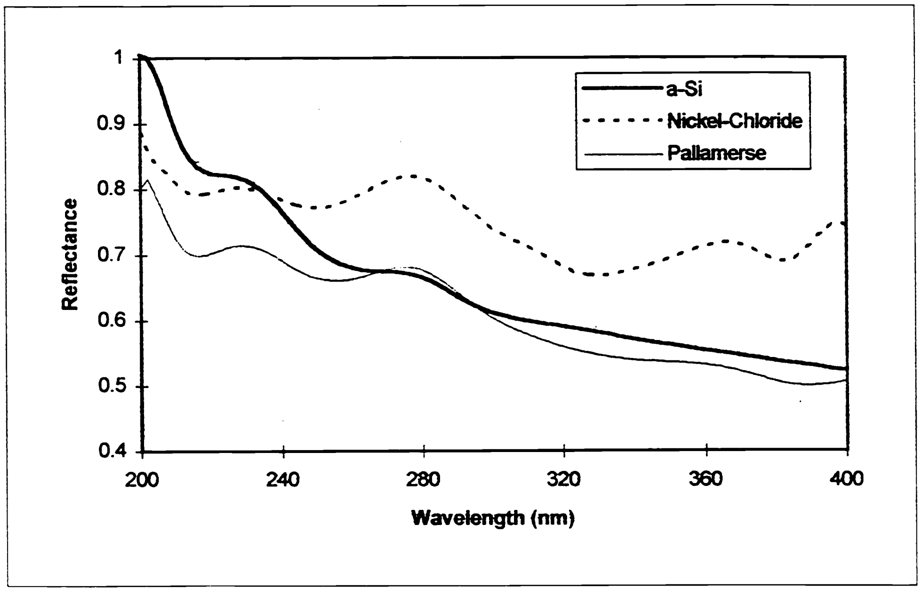


Figure 7 Surface treatments can be used to affect grain size, thermal budget, and the physical properties of the resulting poly-Si films. Shown here is the UV reflectance for the fully crystallized films obtained by annealing at 600° C in 10 minutes after pallamerse and nickel-chloride surface treatment. For comparison, the reflectance of the untreated amorphous precursor film is also included. The untreated samples require 24 hours for crystallization.

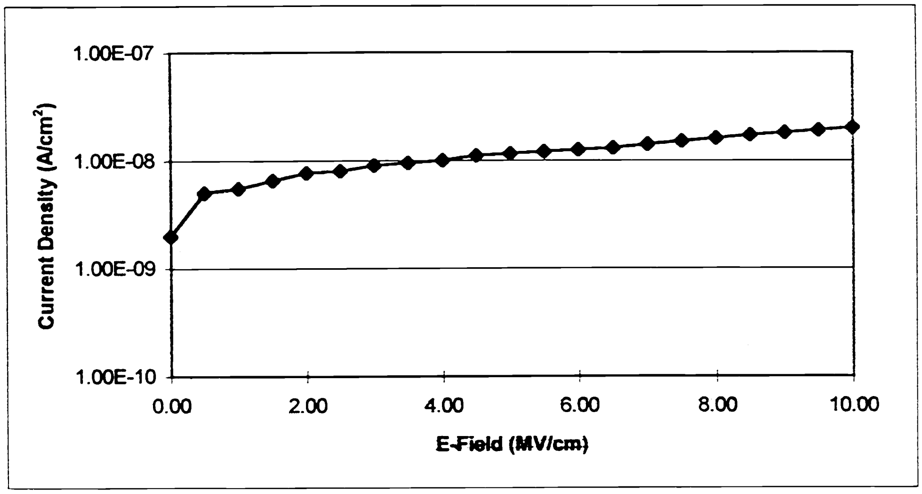


Figure 8 Low Temperature Device Quality ECR-PECVD Silicon Nitride

Downloaded From: http://proceedings.spiedigitallibrary.org/ on 10/10/2016 Terms of Use: http://spiedigitallibrary.org/ss/termsofuse.aspx