35.4: A 2.1-inch AMOLED Display Based on Metal-Induced Laterally Crystallized Polycrystalline Silicon Technology

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Abstract
A 2.1-inch color active-matrix organic light-emitting diode display based on an improved metal-induced laterally crystallized polycrystalline silicon technology is demonstrated. Leakage current was reduced with the active islands of polycrystalline silicon transistors patterned after nickel-based metal-induced lateral crystallization. Color was obtained by combining white-light organic light-emitting diodes with micro-fabricated color filters.

1. Introduction
The demand for flat-panel displays with higher information content and lower power consumption has been driving the development of active-matrix (AM) organic light-emitting diode (OLED) displays [1]. In the realization of AMOLED displays, polycrystalline silicon (poly-Si) and amorphous silicon (a-Si) thin-film transistors (TFTs) have been used as the electronic switching elements [2-5].

The more mature a-Si TFT was not originally considered capable of supplying enough current to drive OLED until Lu *et al*. demonstrated its possibility in 1998 [4]. This has been verified by other research groups [3,5]. However, a-Si TFT suffers from not only low field-effect mobility but also stress-induced instability. OLED is a current-driven light emitting device, requiring at least one “driving” TFT in the pixel circuit which is on during almost the entire frame period. This requires high stability for the TFT. Poly-Si TFT has an advantage over a-Si TFT in this regard. Furthermore, the high field-effect mobility of poly-Si TFTs also allows integration of peripheral circuits with the active matrix on the same glass substrate. This is desirable for portable information displays.

Metal-induced lateral crystallization (MILC) of a-Si is a recently developed low-cost technology to obtain high-performance poly-Si. Its application to monochrome AMOLED was first demonstrated in 2001 [6]. Techniques to improve MILC poly-Si TFT performance and process compatibility with OLED fabrication have been addressed [7-8].

A technique to reduce the leakage current of poly-Si TFT by switching the order of island patterning and lateral crystallization is presented in this paper, and a 2.1-inch color AMOLED display based on the improved MILC poly-Si TFT technology is demonstrated.

2. Reduction of Leakage Current
The leakage current of TFT is a critical parameter, excessive amount of which would result in image quality degradation such as unintentional turn-on of pixels. Besides grain boundaries, residual nickel in an MILC poly-Si TFT active island may also have an undesirable influence on TFT leakage current.

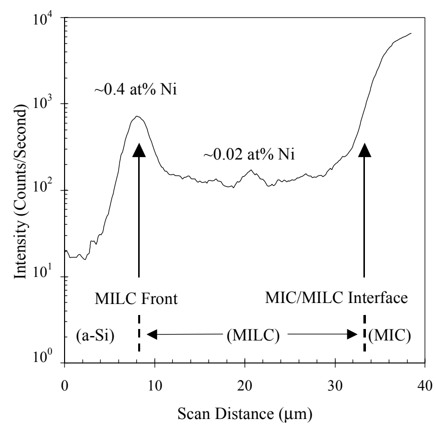

Figure 1. Distribution of nickel concentrations in different regions of MILC poly-Si thin film

From the nickel distribution shown in Figure 1 [9], it is clear that nickel concentration is the highest within the MIC region and the lowest within the MILC region. The nickel concentration at the MILC front is much higher than that within the MILC region. This implies that MILC poly-Si resulting from non-patterned a-Si thin film will have different states of crystallization and different distribution of nickel concentration. Consequently, TFT based on this MILC poly-Si will have different characteristics, when compared to that resulting from patterned a-Si island with edge confinement. Two types of TFTs were fabricated in the same process to study the effects of switching the order of island patterning and lateral crystallization, one (Type A) with active

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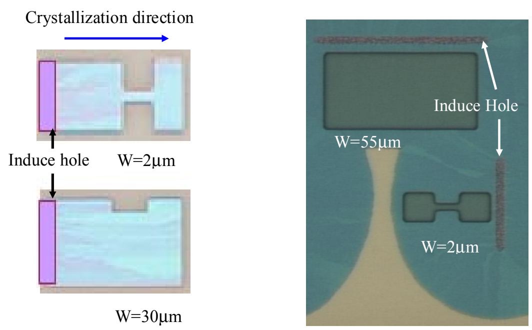
islands formed before MILC and the other (Type B) with active islands formed after MILC.

Photographs of the active islands of Types A and B TFTs are shown in Figure 2a and 2b, respectively. For Type A TFTs, the stripes on the left hand sides of the active islands are the MIC regions, located within the crystallization-inducing holes. The MILC fronts with high nickel concentration moved right with the crystallization and stopped at the right most edges of the active islands.



(a) (b)

Figure 2. Photographs of active islands patterned (a) before and (b) after MILC

For Type B TFTs, the dark green regions are covered with photoresist. Removed from the active islands are the MILC/MIC interface and all MILC fronts with high residual nickel concentration. It can be readily seen in Figure 2b that the direction of MILC is not necessarily parallel to the channel conduction direction.

The transfer characteristics of Types A and B TFTs with channel width/length of 12µm/5µm are shown in Figure 3. Both types of TFTs exhibit high mobility of ~100cm^2/Vs, steep sub-threshold slope of ~0.7V/decade and threshold voltage below 5V. However, the leakage current behavior was quite different.

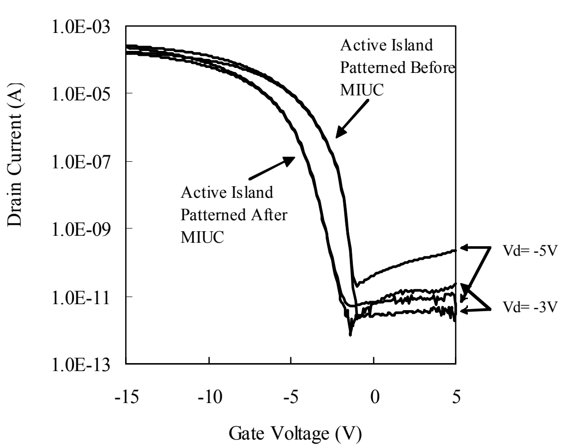


Figure 3. Transfer characteristics of p-type MILC poly-Si TFTs with active islands patterned before and after MILC at different drain bias voltage V_d.

For Type A TFTs with active islands patterned before MILC, the minimum leakage current for a TFT with channel width/length of 12µm/5µm is about 24.5pA at a drain voltage (V_d) of -5V. The transfer characteristics also reveal that Type A TFTs have high gate-induced leakage current, which is as high as 212pA at a gate bias (V_g) of 5V and a V_d = -5V. For Type B TFTs with active islands patterned after MILC, the minimum leakage current for a TFT at V_d = -5V with the same channel width/length ratio is 5.25pA. A reduced dependence on V_g is also evident. The leakage current is about 10.8pA at V_g = 5V and V_d = -5V.

Shown in Figure 4 is the dependence of the average minimum leakage current per unit channel width on the channel width at V_d = -5V and the average leakage current per unit channel width at V_d = -5V and V_g = 5V.

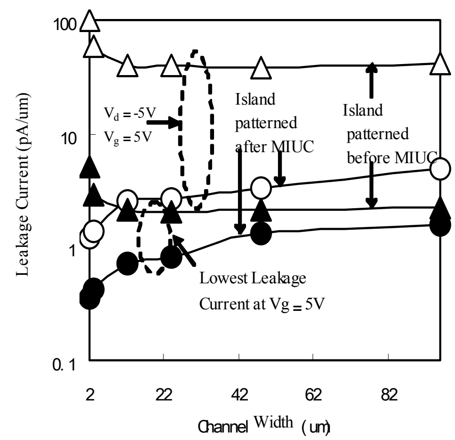


Figure 4. Dependence of the leakage current per unit channel width on the channel width of Types A and B TFTs.

The average leakage current per unit channel width of Type B TFT is much lower than that of Type A TFT. This is particularly true for TFTs with small channel width of 2 and 3µm. The difference between the leakage currents per unit channel width can be almost 2 orders of magnitude.

These results show that leakage current is reduced by defining active islands after the MILC process, without increase in process complexity and cost. It is presently suggested that the reduction of leakage current resulted from the removal of regions containing relatively high concentration of nickel residual. However, if the channel width is larger than the length of the crystallization-inducing hole, MILC will take place along directions not entirely parallel to the direction of channel conduction. This might be the reason for the increased average leakage current per unit channel width as the channel width is increased.

3. Poly-Si TFT Active-Matrix Panel

The relatively uniform characteristics of MILC Poly-Si TFTs allow the implementation of two-TFT voltage-driven pixel architecture in the present 2.1-inch AMOLED display. The width-to-length ratio of the address and drive TFTs are 3µm/5µm and 48µm/5µm, respectively. By "folding" the 0.6pF storage capacitor, its projected area is reduced.

Except for (1) reversing the order of island patterning and (2) replacing low-temperature oxide (LTO) by plasma-enhanced (PE) chemical vapor deposition (CVD) oxide as the inter-level dielectric, the TFT process is the same as that used to implement the previously reported monochrome display.[7] Typical process parameters are summarized in Table I.

Table I. MILC poly-Si TFT panel process and structure parameter.

Active Layer	LPCVD 30nm a-Si, 550oC MILC annealing for 22 hours
Gate Oxide	LPCVD 50nm LTO
Gate	300nm poly-Si
Doping	Boron implantation. Energy: 40KeV, dosage: $4\times10^{15}/cm^2$
Inter-Connecting	Two layers of sputtered Al, 500nm
Insulator between Al connecting layers	PECVD 500nm SiON
Pixel size	90µm ×270µm
Number of scan lines	128
Number of data lines	160×3

Thin active and gate oxide layers were employed to improve the threshold voltage. Silane and nitrous oxide (N_2O) based PECVD at 300°C were used to form the oxide insulation layers beneath the aluminum (Al) inter-connect and between the Al and the indium-tin oxide (ITO) transparent electrode. It was observed that the TFT characteristics were much degraded after the deposition, but could be recovered by annealing in nitrogen at 420°C and forming gas at 380°C, as shown in Figure 5.

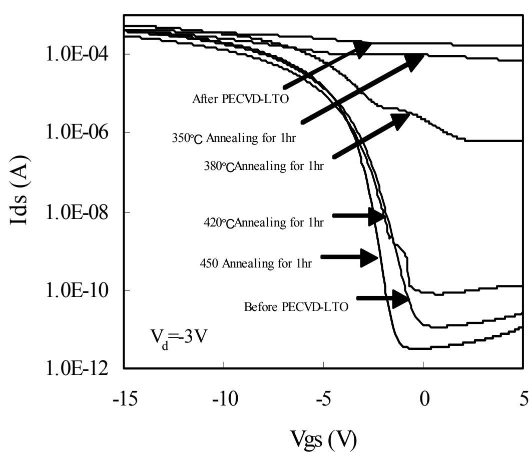


Figure 5. Transfer characteristics of MILC poly-Si TFT before and after the formation of PECVD SiON (The characteristics after nitrogen and forming gas annealing are also shown.)

Typical field-effect mobility (μ_{FE}), threshold voltage, sub-threshold slope and on/off current ratio of the TFTs are summarized in Table II. Since the minimum leakage current occurs at V_g = 0V, it is not necessary to impose a positive V_g to achieve the minimum current. This significantly simplifies the design of the periphery controller and drive circuits.

Table II. MILC poly-Si TFT characteristics

Field-effect mobility	$\sim10^6$ cm^2/Vs
Threshold voltage	>-3V
On/off current ratio	$>10^7$
sub-threshold slope	~ 0.7V/dec

4. Color Filter Fabrication

Photo-patternable color filters (CFs) combined with white-light emitting OLEDs (Fig. 6) were applied to achieve the color display. The size of each color sub-pixel is 90µm by 270µm.

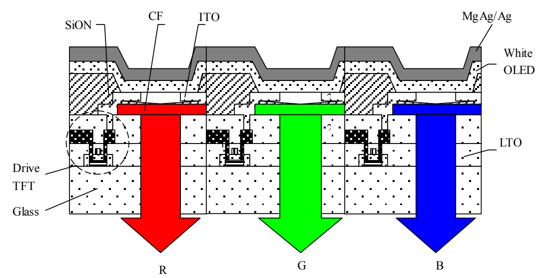


Figure 6. Cross section schematic diagram to achieve color display by color filters and white OLED.

1µm thick red (R), green (G) and blue (B) micro-CFs were made on a TFT panel using spin-coating and photolithography. After the formation of the CFs, an extended oven bake at 180°C for 6 hours was performed for more complete polymerization and to smooth out the edges of the CFs. The latter would improve the step coverage of the subsequently sputtered ITO anode of the white OLED.

The maximum temperature that can be tolerated by the CFs[10] is lower than 230°C. Since the edge profile after an acid-based etching of such low-temperature deposited ITO is generally quite uneven, a lift-off patterning was adopted to eliminate the need for etching-based patterning. Therefore, the 180nm thick ITO anode on CF was deposited using room-temperature magnetron sputtering.

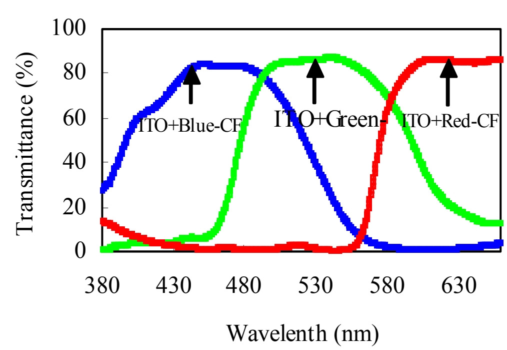


Figure 7. Optical transmissions of CFs covered by the room temperature ITO.

Shown in Figure 7 are the optical transmission characteristics of the micro-CFs covered by room-temperature ITO with a sheet resistance of 120Ω. The respective peaks of R, G and B CFs are located at wavelengths of 630nm, 530nm and 450nm. The corresponding transmittance is higher than 80% of a reference bare glass.

The ITO anode of each OLED is connected to one junction of the corresponding drive TFT through an intermediate Al interconnect buried under the micro-CFs. To prevent the color filter developer from attacking this Al layer, contact holes connecting ITO to Al were opened only after the complete preparation of the micro CFs.

5. Color AMOLED Video Display

The TFT panel surface was planarized using photo-resist to satisfy the roughness requirement of OLED. A photograph of a portion of a TFT panel immediately before OLED formation is shown in Figure 8. The pixel aperture ratio is about 46%.

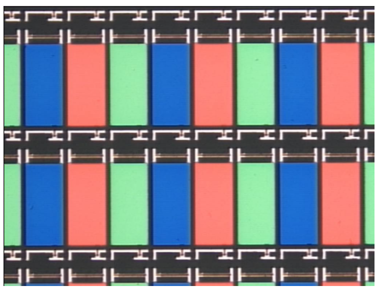


Figure 8. Photograph of magnified RGB pixels.

Figure 9. Photograph of an image displayed on a 2.1-inch MILC poly-Si TFT color AMOLED.

The resulting color AMOLED was driven by signals from the digital video interface of a personnel computer using a “four sub-frame” scheme. 4-bit grey-scale for each color was achieved using different sub-frame durations in the ratio of 1:2:4:8. Consequently, the number of color is 4096. A color picture displayed using the color AMOLED is shown in Figure 9. The picture is clear and exhibits good color saturation.

6. Summary

A 2.1-inch color MILC poly-Si TFT active-matrix organic light emitting diodes with conventional two-TFT pixel circuit has been demonstrated. Careful layout of the TFTs and the storage capacitor resulted in an aperture ratio of 46%. The TFT active islands were patterned after nickel-based metal-induced lateral crystallization to obtain reduced leakage current, while still maintaining high drive current. Color was obtained by combining white-light organic light-emitting diode and micro-patterned color filters. Room-temperature deposited ITO was used to form the anodes of the diodes. Grey-scale was achieved using a sub-frame driving technique.

7. Acknowledgment

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