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Reel to Real: Prospects for Flexible Displays

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Although it is tempting to begin with a standard opening statement like "Flexible displays have been generating much recent interest," the fact is that flexible displays have fascinated people for about 50 years and have been discussed seriously for at least 20 years. The difference now is that display and backplane technology have evolved to the point where reasonably attractive-looking demonstrations of flexible screens are possible.

This has had two effects. It has spurred an intense drive to finally realize the long-time dream of flexible displays. And it also has allowed industry participants to experience directly the real-world challenges of building these displays, rather than granting them the luxury of imagining that products were just around the corner.

Flexible displays may be defined in a number of ways. Here, the following types are included:

- Curved or conformed, but not flexed during use
- Mildly flexible, but not designed for severe treatment such as rolling
- Fully flexible, like paper or cloth

Not included are displays built on plastic but used in a flat, rigid form—such as those employed solely for ruggedness or light weight. (These flat plastic displays have been commercialized in small quantities for cell phones.) An exception is made for dynamic signage due to the use of roll-to-roll manufacturing. Also not included are glass-based panels that use novel display technology, such as electronic books made with electrophoretic ink on glass (e.g., Sony's Librie).

Technology

Flexible displays may be made on metal foil, very thin glass, or a variety of plastics. In a sense, the substrate material plays the pivotal role in the viability of the flexible display as a competitive product offering. Substrate materials are key to meeting cost, performance, reliability, and manufacturing goals for flexible electronics and displays. Rather than starting with form and function, the venture into making flexible displays must begin with the choice of a proper substrate material.

Intrinsic tradeoffs abound. Thin glass (50-200 microns) has excellent barrier and optical qualities and a low price, but is very difficult to handle in manufacturing. Stainless steel foil requires a nontransmissive display technology and cannot handle multiple bends, but is also a good barrier.

Plastic is the key material choice, allowing reasonable tradeoffs in mechanical, optical, and chemical performance. Multilayer "engineered" substrates will be required for most practical applications. Heat-stabilized PET and PEN seem promising for standard flexible displays, and PAR or even PC-based materials could serve in some cases. Major improvements are still needed in thin-film barrier layers (water penetration, durability to flexing).

The electronics may be inorganic or organic. Silicon-based TFTs and metallic leads are easier to fabricate, although changes are needed to do the processes at low temperature (less than 150 C). Organic electronics are preferable for truly flexible displays, but currently suffer from inadequate mobility (it should be at least 0.5 cm^2/V-sec) and poorly developed manufacturing techniques.

The display technology could be a liquid crystal display (LCD), organic light-emitting diode (OLED), electrophoretic type, or several other types. It is technically feasible to make LCDs on plastic, but prospects are dimmer for backlights and color filters that can handle this format. OLEDs have such stringent barrier requirements (less than 10^{-6} g/m^2-day H_2O) that their market entry may be delayed, but color and viewing angle are excellent. Hence, electrophoretic technology, such as that from E Ink, Gyricon, and SiPix, offer the best near-term prospects. These displays are slow (switching time 100s of ms) and lack good color performance, but progress is steady.

Market forecast

The only flexible displays to reach the market so far have been a simple electrophoretic display on plastic, used for in-store dynamic signs in sample quantities, and a curved monochrome LCD on plastic, used for a sports watch. Over the forecast period (through 2010), products are expected in other application spaces, such as consumer electronics, automobiles, and smart cards. This first generation of flexible displays will help fire the imaginations of product designers, perhaps spurring new applications that have not yet been conceived.

The worldwide market for flexible displays is expected to be valued at $311,000 in 2005, rising to nearly $18 million in 2010. More than 25 million units are forecast to be sold in 2010, mainly for smart cards. Dynamic signage will lead in area and value.

This decade will remain firmly in the realm of market experimentation, rather than strong market growth. The manufacturing methods and equipment for flexible displays are very immature at this time. At every step of the fabrication process—from the substrate material through the top barrier layer and packaging—much more development is needed.

Resources for the development of flexible displays are increasingly available. Government sponsorship is common (such as a $43 million Army-sponsored program at Arizona State that includes corporate partners), and many large corporations maintain internal research efforts. The prospect of products is close enough that several small and

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start-up companies are also involved. However, none has emerged as a clear "champion" as flexible displays, devoted to gathering the critical mass needed to grow the industry. Philips is the closest candidate at this time.

Strategy

Prevailing images of flexible displays include roll-up screens, curtain-like displays, and electronic paper that perfectly mimics the humble alternative. These images are compelling and indeed represent valid goals in developing flexible displays. But other reasons exist also, such as making conformable displays, which will be bent or shaped once into a non-planar configuration; making displays that are lighter weight or more rugged; and making use of new manufacturing options that may be significantly less expensive than current techniques.

Thus, the suite of potential advantages for flexible displays is quite broad. And yet, in each case, only a given subset of these benefits is relevant. Companies developing flexible displays must be aware of which benefits their products might bring to the marketplace, and then develop and market them appropriately.

Five major sticking points to the expansion of the flexible displays industry can be identified:

- Acceptable substrate material
- Full color process
- A "champion" leading to critical mass
- Compelling application(s)
- Very low-cost production

These must be addressed before commercialization can blossom.

Conclusion

In strategic overviews such as this one, often more questions than answers are brought up. But it is hoped that the key issues have been touched upon so that players in the flexible industry have an awareness of the significant technology, manufacturing, and competitive challenges on the road ahead.

Flexible displays are just barely reaching the market. The true "first generation" of products is yet to come. It is certainly an exciting time, and it may feel like a vulnerable time, but the industry will grow. It has 50 years of imagination behind it that can finally be manifested technologically. The unfolding will occur fully over more than the coming decade, but those present at this early stage will likely remember these first steps as highly significant.

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Low Temperature Poly-Si TFT Technology

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ABSTRACT

Low temperature poly-Si TFT technology is reviewed and is discussed from a view point of device, fabrication process, and its possibility as FPD (Flat Panel Display) application. After the appearance of crystallization technique of SPC (Solid Phase Crystallization) using FA (Furnace Annealing) or ELA (Excimer Laser Annealing) using UV (Ultra-Violet) beam, the electronic property of poly-Si thin-film, which relates to the crystalinity of the grains, was improved drastically, and the process temperature for the TFT fabrication had been reduced below 600℃ down to 400℃. As a result, improvement of device characteristic of poly-Si TFT such as an enhancement of carrier mobility or a reduction of leakage current has been studied intensively for the application to FPD (Flat Panel Display) on glass. Currently, extensive study is being done in order to realize a more functional SOG (System on Glass). By reducing the TFT process temperature down to 200℃ or below and by modifying a design for the device structure or the circuit in the pixel, O-LED (Organic LED) FPD addressed by uniform poly-Si TFTs is expected to mount on flexible plastic substrate such as on PES (PolyEtherSulphone). The poly-Si TFT has a possibility to develop as a smart system on plastic panel for unique applications as well as the conventional Si LSI in the ubiquitous IT (Information Technology) era.

1. INTRODUCTION

Si TFT has been developed remarkably in the last 20 years and plays an important role for FPD application. The Poly-Si TFT had been developed for high-resolution LCD panel with peripheral circuit on quartz glass using high temperature process.[1)] Subsequently, the LTPS (Low Temperature Poly-Si) TFT on low-cost glass was also applied to LCD panel with peripheral circuit, and has a further possibility for highly functional system i.e. SOG.[2)] For the AM FPD panel, O-LED Display of direct emission as well as LCD of indirect emission has been actively reported. The poly-Si TFT performance can be improved by optimizing the device structure and the effective crystallization process such as SPC,[3, 4)] ELC (Excimer Laser Crystallization) or MIC (Metal Induced Crystallization). Poly-Si TFT can be realized not only on glass but also on flexible metal or plastic. In order to realize more flexible and functional FPD, many efforts are being done on further reduction of the process temperature and the improvement of the device characteristic. On the other hand, following a trend of lowering the voltage and shrinkage of device size by a requirement of display with high resolution, a uniformity issue including reliability for the TFT becomes important. In particular, pixel in AM FPD requires uniform and stable characteristics of TFT for the driving. An optimum TFT structure such as the channel, the gate oxide, and the source and drain including the under substrate design should be considered from a viewpoint of lower temperature process.

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2. IMPROVEMENT OF Si TFT USING LOW TEMPERARURE PROCESS

2-1 Relating to the interface (Si/SiO_2)

Many efforts have been done to realize a high performance LTPS (Low Temperature Poly-Si) TFT with high on-current and low off-current. In order to improve the TFTs as a CMOS application, detailed study on carrier conduction should be done. Sharp sub-threshold swing and high on-current are the important factor for the TFT.

The sub-threshold swing behaviour depends strongly on the existence of trap states due to the defects in the Si film and at the SiO_2/Si interface. In order to get a sharp gate voltage swing, reducing the trap states density in Si film and at the interface of Si/SiO_2 is effective. As a result, threshold voltage can be controlled effectively in low voltage. In the weak inversion region, gate voltage swing (S) of TFT is given simply by,[4, 5)]

$$S = (kT/q)\,(1/\log_{10}e)(1+qdN^*_T/C_{ox})$$

$$= (kT/q)\,(1/\log_{10}e)\{1+q(dN_{T+}N_t)/C_{ox}\} \qquad (1)$$

N^*_T : Effective trap states density ($cm^{-3}\,eV^{-1}$)
N_T : Trap states density in Si film ($cm^{-3}\,eV^{-1}$)
N_t : Trap states density at Si/SiO_2 interface ($cm^{-2}\,eV^{-1}$)

In order to obtain a sharp inverted characteristic in sub-threshold region, enlarging the oxide capacitance or decreasing the channel thickness as well as reducing the effective trap states density is important. As a result, controllability of V_{th} in low voltage is improved. In order to decrease the trap states density in the Si films or at the SiO_2/Si interface, improving the crystallinity in the Si channel, an introduction of dense SiO_2 film and terminating hydrogen atoms to the dangling bonds in the Si films are considered. In the case of N^*_T=0, S gives an ideal value of 60 mV/dec. (at R.T.), which corresponds to the S value for single-crystalline FD SOI (Fully Depleted Silicon on Insulator). High quality silicon dioxide films are deposited by CVD using HDT (High Density Plasma) sources such as ECR (Electron Cyclotron Resonance) or ICP (Inductively Coupled Plasma). Gate oxide film, which is deposited using the ICP CVD below 200℃, can realize improved C-V curve and high breakdown voltage over 8 MV/cm due to low interface trap density of smooth Si/SiO_2 interface and small number of carrier trapping site caused by a presence of less hydrogen. Single-crystal SOI TFT formed by low temperature process below 400℃ using the ICP SiO_2 as a gate oxide shows high mobility and sharp gate voltage swing as shown in Fig.1.[6)]

2-2. Effective crystallization and enhancement of drain current

Conduction current in poly-Si TFT depends not only on the device geometry (L, W, t_{ox}) but also strongly on the carrier mobility relating to the crystallinity in the film.. In order to increase a value of the field-effect mobility, high temperature thermal annealing or ELA, and subsequent effective hydrogen annealing for the Si channel are necessary so as to decrease the defects density at the grain boundaries or inside the grains in the Si film as well as at the Si/SiO_2 interface.

For the poly-Si films with comparatively small grain size, existence of high trap states density suppresses the drain current. RTA (Rapid Thermal Annealing) at high temperature improves the device characteristics. Single-shot ELA improves the current drivability remarkably with keeping the grain size small.[7] As the localized defective regions in the films can be preferably melted by a shot of ELA, improvement in grain boundary or small defects is distinct. Currently, uniform and rather higher carrier mobility than the value of a-Si:H TFT is required for driving a pixel in AM O-LED. Small grained poly-Si TFT with uniform characteristic such as micro-poly-Si TFT is favorable for the O-LED driving.

After long time of FA (Furnace Annealing) for amorphous Si films at around 600°C, large crystalline grains of dendrite shape (~ 1μm) can be obtained.[3, 4] (Fig.2) After the SPC, electrical barrier height for electrons at the grain boundaries is very low[8] as well as the film obtained by ELA. Although resultant drain current becomes high, there are still remained many small defects such as dislocation or twin boundaries. By performing an ELA subsequently after the SPC, the crystallinity improves, i.e. the trap states density due to the small in-grain defects decreases. In particular, ELA of controlled energy, which can melt mainly the defective region in the Si film instantaneously, improves the crystallinity in the large grains and the TFT characteristic.[9, 10] Advantage of the typical crystallization methods is compared as in Table.1.

Table 1. Comparison of effective crystallization techniques (O: Good, X: Poor)

	SPC	ELC	(MIC)
Grain size	O	Δ	O
Crystallinity	Δ	O	Δ
Flatness	O	Δ	
Uniformity	O	Δ	
Throughput	X	O	Δ
Growth model	O	Δ	
Process temperature	~600°C	**<400°C**	~500°C

On the other hand, in order to realize a lower temperature process, poly-SiGe channel using SPC has been proposed for TFT fabrication. By modifying the interface structure as $SiGe/Si/SiO_2$, getting higher current with sharp voltage swing is possible by suppressing the interface scattering.[11] Ni induced crystallization technique (MIC), which accelerates the lateral SPC speed, has also been studying intensively as a lower temperature process.[12, 13] By incorporating Ni into the Si films, a few microns of needle-like long grains can be obtained.

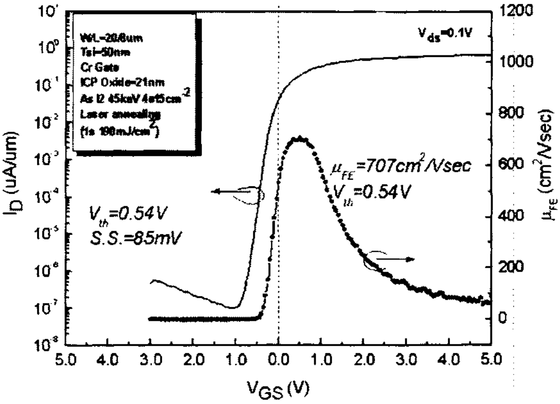

Fig.1. Transfer curve of SOI TFT using ICP SiO_2 as a gate oxide.[6]

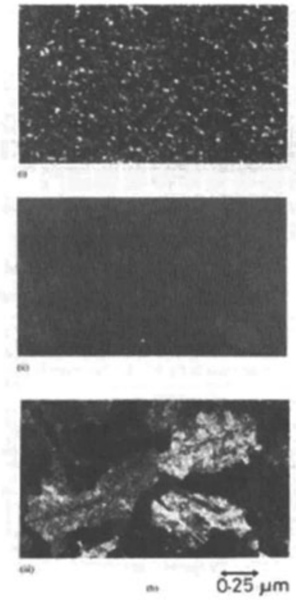

Fig.2. A reported TEM image of dendritic grains from amorphous phase.[4] **(SPC)**

Excimer laser with UV (Ultra-Violet) pulsed beam can heat up only Si surface or thin Si layer without giving a heating damage under substrate. Direct ELC on amorphous Si has been studied intensively. In order to get a larger grain size, ELC with heating of substrate is effective, so as to control its solidification velocity.[14, 15] Also, notable lateral grain growth by optimizing the energy condition with multi-shots ELC or ELA has been reported.[16, 17, 18] (Fig. 3) Lateral crystallization effect under thermal slope is drastical.[19, 20] As the ELC of sufficient energy density can melt the Si films, the grain boundary barrier height for the laser annealed films is low as well as for the films after SPC, and the crystallinity in the grains for the film of ELC is better than that for the case of only SPC although the surface flatness should be inferior.

In order to produce the maximum performance of TFT characteristics, optimum process are required for the thin source and drain and for the gate electrodes of low resistivity and of the ohmic contact. Efficient activation, doping and/or silicidation compatible with low temperature process have been studied.[21, 22, 23)]