Thin Film Transistor Technology—Past, Present, and Future

by Yue Kuo

Although liquid crystal displays (LCDs) have been available for over half a century, they were always taken as niche market products because of their rather poor performance: small viewing angles, long response time, and lack of large-area panels. The situation has changed drastically since the availability of the active matrix (AM) LCDs, specially the amorphous silicon (a-Si:H) thin film transistor (TFT) driven LCDs. For example, worldwide revenue of the TFT LCD improved from about $1 billion in 1989 to near $110 billion in 2012.[1] The main producers expanded from Japan to the surrounding Asia Pacific countries, such as South Korea, Taiwan, and China. The shipment of LCD TV units from 2011 to 2012 was predicted to increase by 9% to 225 million units.[2] In the early mass production stage, TFT LCDs were used in high price products, such as computer monitors, games, and instruments. Later on, due to the gradual maturity of the production technology, TFT LCDs were applied to consumer electronics, such as TVs and mobile phones. At the same time, researchers were investigating new types of TFTs to solve some of the intrinsic device performance or production problems. Furthermore, applications of TFTs beyond pixel driving in the LCD have been explored. Therefore, this is a good time to review the history and progress of the TFT technology as well as to predict possible future development trends.

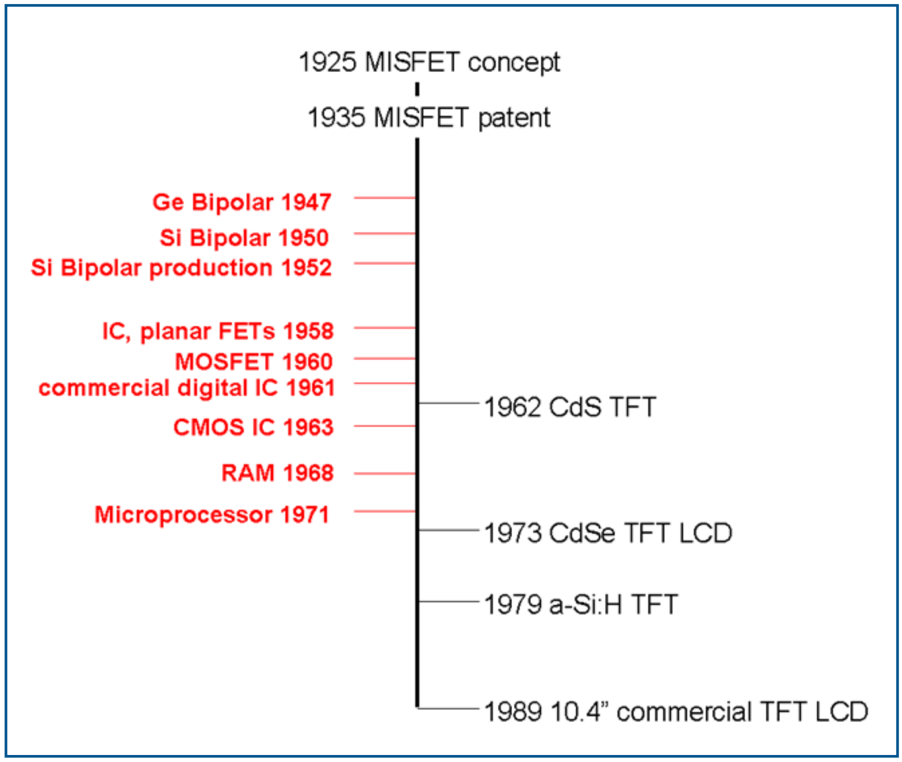

Fig. 1. *History of TFT and IC development.*

Pre Mass Production of Large-Area TFT LCDs—Before 1990

The TFT is a field effect transistor (FET). Its structure and operation principles are similar to those of the metal oxide field effect transistor (MOSFET), which is the most critical device component in modern integrated circuits (ICs). The development histories of TFTs and MOSFETs are similar, as shown in Fig. 1. The metal insulator semiconductor field effect transistor (MISFET) conceptually was born in 1925.[3] The early popular TFT versions were made of compound semiconductors, such as CdS or CdSe.[4,5] This kind of TFT has a high field effect mobility, μ_{eff}, *e.g.*, > 40 cm^2/Vs. The CdSe TFT LCD was first demonstrated in 1973.[5] However, mass production of this kind of LCD on large-area substrates has never been realized. Among many possible reasons, complications in controlling the compound semiconductor thin film material properties and device reliability over large areas are often discussed.

The breakthrough in the field came from a report in 1979 of the first functional TFT made from hydrogenated amorphous silicon (a-Si:H) with a silicon nitride gate dielectric layer.[6] Figure 2 shows the (a) structure and (b) transfer characteristics of the first a-Si:H TFT (6). The fabrication process is simple and the device is stable at room temperature under atmospheric conditions. The composing films were deposited by plasma-enhanced chemical vapor deposition (PECVD), which can be easily carried out on commercial, large-area, low-temperature glass substrates with high throughput.

The a-Si:H TFT has a $\mu_{eff} < 1$ cm^2/Vs, an off current (I_{off}) of < 10^{-12} Amp, an on-off current ratio (I_{on}/I_{off}) of > 10^6, a threshold voltage (V_t) of < 3 V, and a subthreshold slope (S) of < 0.5 V/dec. These characteristics are good enough for pixel LC switching in a display, which is typically operated at 120 Hz or less. There are a few drawbacks in the a-Si:H TFT device. First, the mobility is too low for high-speed or large-current applications, such as the driving circuit of the display or the pixel driving in the organic light emitting diode (OLED) display. Hence, the gate and data signals of the AM LCD have to be supplied by IC chips bonded to the periphery of the panel. Second, since a-Si:H is a photoconductor, the TFT has a large leakage current under light exposure conditions. This problem is solved by covering the TFT with an opaque material. This light blocking material is also prepared into a black matrix form around all pixels to prevent light leakage from adjacent pixels. Third, the stability of the TFT, *e.g.*, the V_t shift under extensive stress condition, has been a concern. Many strategies, such as the application of a reverse bias voltage, have been used to solve the problem.

The a-Si:H TFT was recognized as the most suitable device for large-area AM LCDs immediately after its invention. Almost all major electronics companies in the world have been involved in R&D activities on this device with the common goal of realizing mass production of high performance flat panel displays. Figure 3 shows the common structure of a TFT LCD. The major composing elements are the back panel, an LC layer, a color filter front panel, polarizer layers, a back light, etc.[7] The back panel contains a large number of pixels connected with horizontal (gate) and vertical (data) lines. Each pixel includes a TFT to which a charge storage capacitor is attached. In the display area, the panel size, which

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is the diagonal dimension of the panel, is commonly expressed in the unit of inches. Therefore, for the rest of this paper, in order to match literature reports, the size of the LCD is shown as “inch” instead of “cm” or “m.” In the mid-1980s, small size a-Si:H TFT LCDs, *e.g.*, 5-inch displays, were available for games and instruments. In the late 1980s, the Hosiden Company supplied black and white TFT LCD panels to Apple Computers. However, the first large-area, color TFT LCDs, *i.e.*, the 10.4-inch VGA (640 x 480 resolution) panels, were mass produced by DTI (Display Technology Inc.), which was a joint venture of IBM and Toshiba. Around the same time, other companies, such as Sharp, Hitachi, NEC, Matsushita, Sanyo, and ADI introduced similar products. At the same time, some American and European companies and universities were actively involved in R&D activities and greatly contributed to the understanding of the device physics and process technology. However, few large-scale production facilities were built. Therefore, the era of mass-production of large-area TFT arrays started about ten years after the first publication of the a-Si:H TFT paper.

Technology development enabling the mass production of large-area TFT LCDs was led by industry R&D groups with many universities participating in the research activities. The supply chain for the complete display production including LC materials, process equipments, drivers, and associated materials was established during this period of time. Because the TFT array is the most critical part of the AM LCD, most R&D efforts were focused on solving critical production challenges, such as the following.

- *Identification of the proper TFT structures.*—Due to the flexibility in the thin film deposition process, TFTs can be prepared as various structures, *e.g.*, depending on the relative position of the gate and the source/drain electrodes and whether a channel passivation layer is required. Based on experimental results and electrical characteristics, *e.g.*, with respect to μ_{eff}, I_{off}, I_{on}/I_{off}, S, V_t, and reliability, inverted, staggered bi- and tri-layer structures, as shown in Fig. 4a and 4b, were identified as most suitable for the a-Si:H TFT. On the other hand, the coplanar structure, as shown in Fig. 4c, was most suited for the poly-Si TFT device.
- *Understanding of basic device physics and reliability.*—Modeling and experimental work has been carried out extensively on TFTs fabricated from different processes. Influences of the semiconductor band structure, gate dielectric defects, interface density of states, etc. on device characteristics, lifetime, failure mechanism, etc. were studied. Solutions to the long-term device stability, *e.g.*, the driving methods and bulk or interface material properties, were identified.
- *Establishment of basic fabrication processes and identification of large-area production equipments.*—Unit processes, such as PECVD, RIE, sputtering, and lithography, and substrate transfer and cleaning methods have been evaluated. All processes were developed to satisfy the large-area production requirements, such as high deposition rate with good uniformity, large etch selectivity, and high stepper resolution and throughput. Processes were optimized through experiments for device performance and stability. The first generation glass substrate, *e.g.*, 30 cm x 40 cm, was used in equipment design and production.

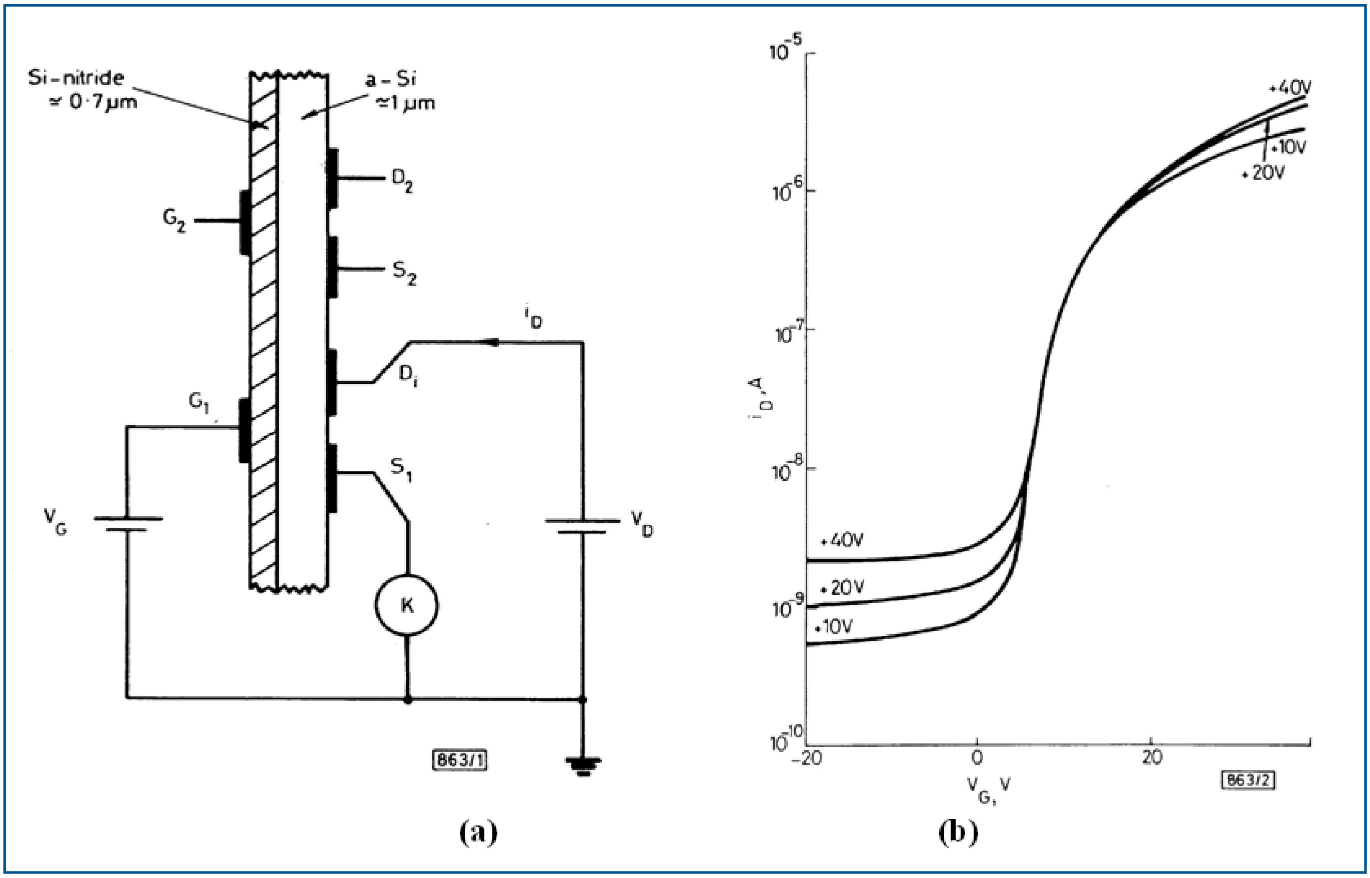

Fig. 2. *First a-Si:H TFT structure and transfer characteristics.*[6]

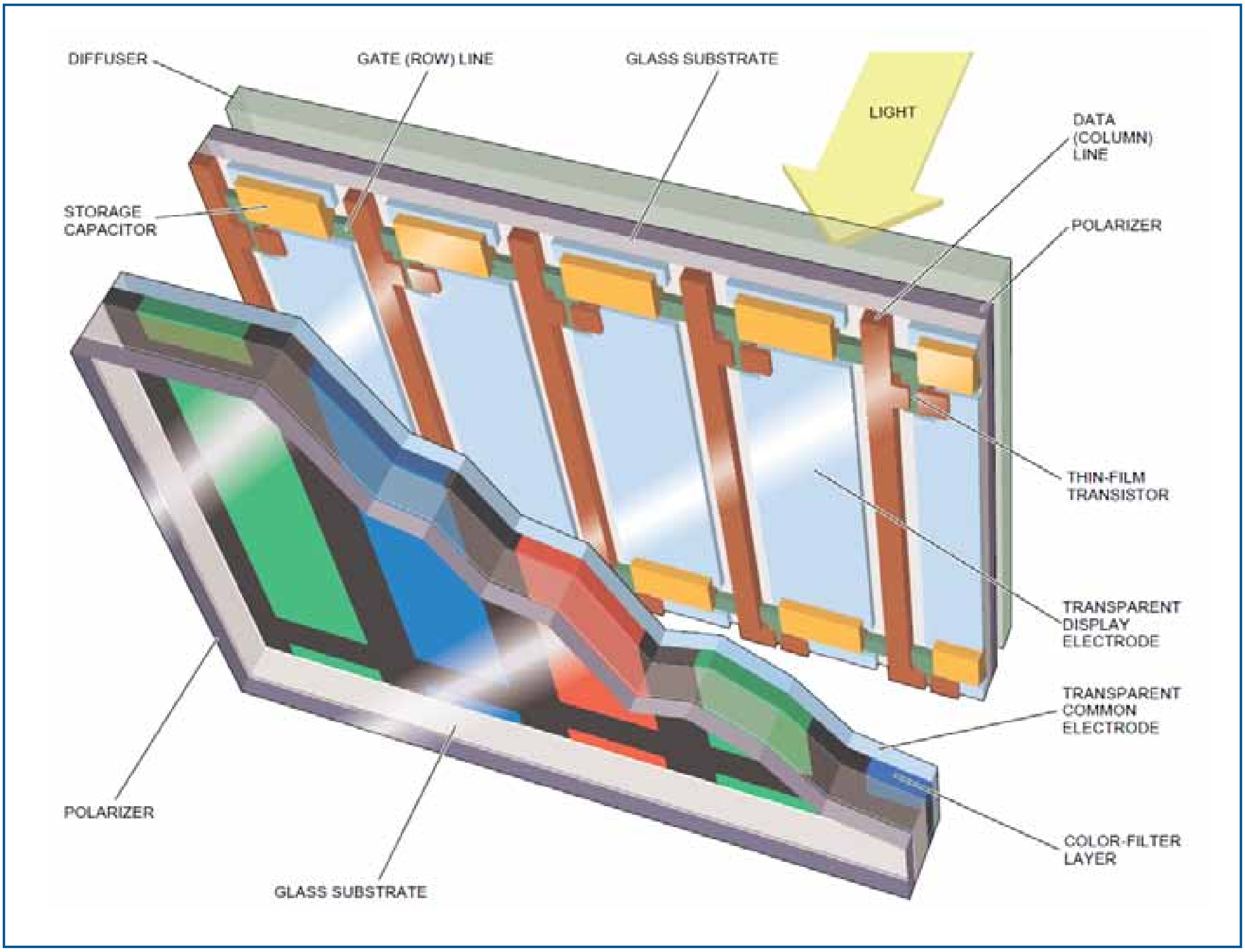

Fig. 3. *Schematic of a TFT LCD structure.*[7]

In contrast to the IC industry, although the general requirements for the device characteristics and thin film material properties have been identified in this period of time, different companies have chosen TFT structures and developed their own, customized deposition and etching process versions.

Mass Production and Technology Advancement—1990 to 2010

Spurred by the great success of the introduction of TFT LCDs to laptop computers, the industry has focused its efforts on consumer products, specifically large-area TVs. For example, 55- to 65-in TFT LCD TVs are widely available on the market today. Most of these panels have very high resolution, *e.g.*, HD (1920 x 1080). The 108-in direct-view TFT LCD, as shown in Fig. 5, was demonstrated by Sharp in 2007.[8] A small share of products, *e.g.*, small-size, high-resolution displays, were fabricated based on poly-Si TFTs. At the same time, a number of medical X-ray imagers were manufactured based on large-area a-Si:H TFT arrays. Technologies related to these products, such as LC or scintillation materials and panel designs, have been improved accordingly.

During this period, industry activities were focused on increasing throughput, lowering production cost, and enlarging panel size. Products were dominated by a-Si:H TFTs. For example, the main achievements include the following.

- *Enlargement of the glass substrate size.*—The glass substrate size has been constantly enlarged, *i.e.*, from the 1st generation of 30 cm x 40 cm to the 10th generation of 2.88 m x 3.15 m. On average, the substrate size was increased at the rate of 30%/yr, which is consistent with the growth rate of the wafer size in the VLSIC industry.[9] It enables the production of the large-size TFT array and the inclusion of a large number of displays on each substrate, both of which lower the production cost and increase the production throughput. For example, only three pieces of the 32-in TFT array can be fabricated on each 5th generation glass substrate while six pieces of the 65-in TFT array can be built on each 10th generation glass substrate. The thickness of the glass substrate was reduced with the increase of the substrate size. However, the size of the glass substrate used in the industry has never been unified.
- *Evolution of production equipment.*—TFT process equipment has evolved for several generations to adapt to the enlargement of the glass substrate and to improve the process speed, *e.g.*, with respect to the deposition rate and the substrate handling time, and yield, *e.g.*, for less particle generation and better surface cleaning.
- *Simplification of the fabrication process.*—The TFT array production throughput was improved by reducing the number of masking steps, *e.g.*, from seven to five or four masks, often in combination with self-aligned structure. At the same time,

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the aperture ratio of the pixel, *i.e.*, percentage of the light transmission area, was increased through the new layout design or the reduction of the critical dimension. The panel's power consumption, brightness, and contrast ratio were improved accordingly.

- *Knowledge of the large-area process chemistry, physics, and limits.*—For example, material properties of the slightly N-rich SiN_x gate dielectric for the low V_t a-SiH TFT was identified.[10] This information could shorten the start-up time of a new production line. In addition, the complicated relationship among the PECVD process, the SiN_x properties, and the large-area film thickness uniformity were delineated using the critical power concept.[11] This result determined the practical achievable deposition rate. Separately, high etch selectivity between the n^+ and the intrinsic a-Si:H was achieved with the Cl-based RIE process.[12] This process increased the yield and broadened the process window of the bi-layer TFT. Furthermore, radiation damage mechanism of the RIE process and the TFT repair method were disclosed, which was critical to high production yields.[13] Recently, a plasma-based, room-temperature copper etch process was developed, which enabled the production of high-resolution, large-area displays.[14,15]

In the same period of time, new TFTs with applications beyond pixel driving in the LCD panel have been reported, as shown in the following two categories.

- *Advancement of Si-based TFT technology.*—Although progress of the large-area poly-Si TFTs fabrication lags behind that of the a-Si:H TFT counterpart, there were continuous efforts in breaking the technology bottleneck. For example, the conventional a-Si-to-poly-Si crystallization process was restricted by the high thermal budget or the long process time. To solve this problem, metal-induced crystallization and pulsed rapid thermal annealing methods have been introduced.[16,17] The former's process speed is still too slow, *e.g.*, > 10 hours at 500ºC, and the latter's grain quality can be improved. On the other hand, reports have emerged of fabricating TFTs on high quality poly-Si thin films prepared using delicate and complicated laser exposure techniques.[18,19] Functional driver circuits and even complete system-on-glass, *i.e.*, including the CPU, memories, and I/O circuits, have been demonstrated.[19]

Separately, new functions or applications of TFTs have been reported. For example, the a-Si:H TFT has been made into a nonvolatile memory device using the floating-gate structure.[20] Also, TFT-based chemical, electrical, optical, biological, and magnetic sensors or detectors have been demonstrated by altering the transistor structures, composition of the thin films, attached devices, etc., as shown in Table I.

- *Alternative semiconductor materials for TFTs.*—There are constant efforts in searching for new types of TFTs to improve performance or to lower the production costs of Si-based TFTs. For example, although the a-Si:H TFT arrays are routinely manufactured at low temperatures, *e.g.*, 300ºC, the critical steps are done with vacuum processes, *i.e.*, PECVD, sputtering, and RIE. If they are replaced with non-vacuum processes, the production cost may be further reduced. On the other hand, there is lack of an effective large-area production process for the high mobility with good reliability

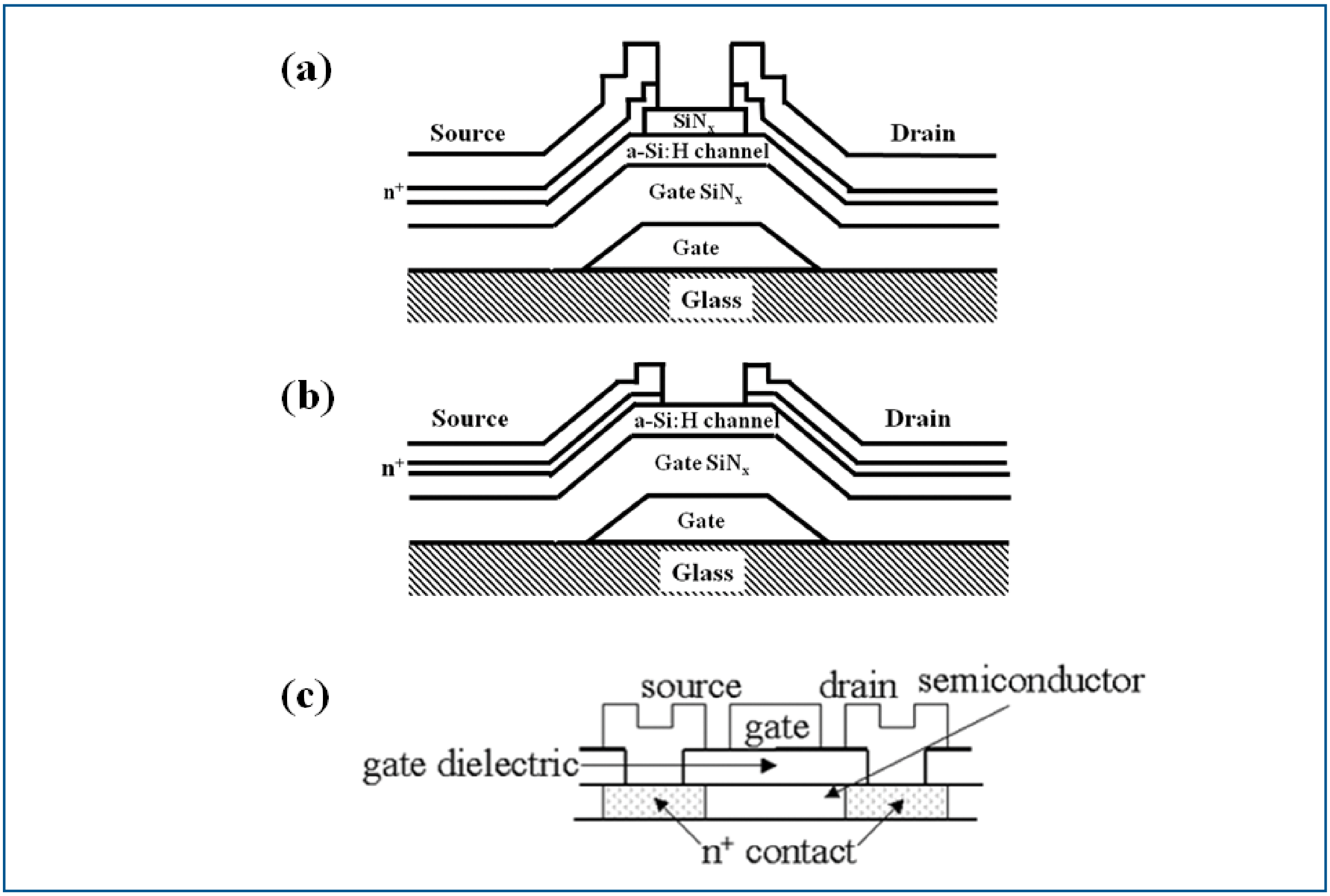

Fig. 4. *TFTs with inverted staggered (a) tri-layer and (b) bi-layer structures, and (c) coplanar structure.*

Fig. 5. *108-in (93.9 in x 52.9 in) TFT LCD with 1,920 x 1,080 resolution made by Sharp and demonstrated at the Computer Electronics Show, January 8-11, 2007.*[8]

poly-Si TFT. If a new type of TFT that has the high mobility and can be fabricated with a low thermal budget, it can replace the poly-Si TFT in many applications.

The organic TFT (OTFT), which is a p-channel transistor, has been proposed as an alternative to the a-Si:H TFT because the polymeric semiconductor thin film can be spin-coated, printed, or casted on the substrate at room temperature without using vacuum equipment. There are many choices for organic semiconductor materials, some of which have been made into TFTs with higher field effect mobilities than that of the a-Si:H TFT.[21,22] However, there exist many challenges in this area. To achieve good TFT characteristics, the organic molecules need to be aligned well at the interface or formed into large, low-defect grains, which is not trivial work. Usually, OTFTs made of small organic molecules, such as pentacene, have better characteristics than those made of large molecule polymers. The small organic molecules are deposited by the vacuum method, such as thermal or e-beam evaporation. The stability of the OTFT in the air is another common concern. These challenges may become more serious when TFTs are fabricated in an array form on the large-area substrate. Additionally, high-quality inorganic gate dielectric materials are used in most OTFTs. The high mobility OTFT often requires a large driving voltage, *e.g.*, > 60V. There are many research efforts in solving these problems. On the other hand, there is great flexibility in tailoring organic molecules, *e.g.*, including various functional groups to the backbone or side chains, which is desirable for many sensing and flexible electronic applications.

Amorphous and crystalline metal oxide TFTs (oxide TFTs), especially those based on ZnO semiconductor material, have attracted tremendous attention in recent years.[23,24] They usually have high field mobilities and can be fabricated with the sputtering method. The complete oxide TFT can be transparent when the source, drain, and gate electrodes are made of ITO or similar types of transparent conductors. Many high mobility oxide TFTs have large leakage currents, *e.g.*, $I_{off} > 10^{10}$ A. Low values for I_{off} have been obtained for In- and Ga-doped ZnO, *i.e.*, IGZO, TFT, which has a mobility about one order of magnitude larger than that of a-Si:H TFT. Nevertheless, this kind of mobility is high enough for some circuit applications or to drive the OLED.

Oxide TFTs are sensitive to humidity, ambient atmosphere, light, and the storage time. These problems could be solved with proper process conditions and an adequate passivation (and light blocking) layer. Oxide TFTs have also been prepared using the solution spin coating method but their device characteristics are not as good as those prepared from the sputter deposition method. Since the doped oxide contains multiple components, the process window for high performance TFTs can be narrow. For LCD pixel driving in the large-area panel, from process control and cost point-of-view, it will be a serious challenge to replace the a-Si:H TFT with oxide TFT. However, since

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Table I. Applications of TFTs in non-LCD applications.

TFT Area	Functions	Principles of operation
Gate dielectric	pH sensing	H^+ adsorption in suspended gate dielectric structure
	Memory	PZT gate dielectric
Semiconductor	Gas sensing	H_2O, alcohols, N_2O adsorption on semiconductor layer
	IR detection	I_d = f(temperature)
Gate electrode	Gas sensing	H_2 decomposition on Pd gate electrode
	Bio sensing	Biomolecule reaction with agents on gate electrode
S/D electrodes	Protein/DNA analysis	Contact resistance change due to biomolecule adsorption
	Artificial retina	Photoconductivity change on attached a-Si:H layer
	X-ray imaging	Scintillator light emission on attached diode
	LEDs	Quantum dot light emission
Structures	Photo sensing	I_{light}/I_{dark} ratio enhanced by split or offset gate
	Memory	Floating-gate dielectric
	Magnetic	Hall effects due to additional electrodes

oxide TFTs can be used in both pixel driving and periphery drivers, the panel production cost can be low if reliability is not a concern. High mobility oxide TFT is also useful in many non-display applications.

Future TFT Development Trends—After 2010

Since most of the TV market in the world is still occupied by CRTs, there is plenty of growth space for TFT LCDs. Therefore, displays will be the main driving force for the advancement of the TFT technology in the foreseeable future. Although the performance of current TFT LCDs is satisfactory for most consumers, the production costs can be further reduced. For the TFT array fabrication part, this means a continuous push for higher yield and throughput. The current trends in reducing the masking steps, shortening each unit process time, widening process windows, and eliminating sources of contamination, will continue. The cost, yield, and reliability of the large-area array process will determine if oxide TFT can replace a-Si:H TFT for LCD applications.

It is difficult to predict in which areas or products, *i.e.*, beyond LCDs, TFTs will have big impact in the future. However, all new developments will be based on the unique characteristics of TFTs. For example, TFTs can be fabricated on various types of rigid or flexible substrates, *i.e.*, there is no need for an (expensive) single crystal wafer. There is no limit to the size or material properties of the substrate as long as it can stand the fabrication process environment. In addition, TFTs can be made from a wide range of semiconductor and dielectric materials. The structure and shape of the TFT are also adjustable. Furthermore, TFTs can have low or high field effect mobilities, *e.g.*, from < 1 to > 600 cm^2/Vs, depending on the material, structure, and fabrication process. The following are some key impact areas for TFTs.

- *Flexible electronics.*—TFTs formed on bendable substrates, *e.g.*, polymers or metals, can be used in displays, imagers, artificial prosthesis, instruments, etc. Depending on the specific application, the requirement for the mobility may be low or high. There are many demonstrations that TFTs can be successfully fabricated on large, flexible substrates using the vacuum or non-vacuum processes. Nevertheless, the major challenge is reliability, especially deterioration of the device characteristics with respect to the bending curvature and frequency. Organic TFTs may be more advantageous than inorganic TFTs due to their flexible morphology. On the other hand, with proper tailoring of the substrate material or structure, a-Si:H, poly-Si, or oxide TFTs may be made into flexible electronics with high reliability.
- *Integrated circuits.*—Instead of competing with single crystal Si based ICs on a small die size, TFTs can be made into logic, memory, and I/O circuits integrated with sensors, imagers, displays, etc. on large substrates. However, since the circuit requirements are more stringent than those of the pixel with respect to density, defects, interconnections, etc., the manufacturing challenges will reside with process yield and economy. Poly-Si or oxide TFTs are necessary for high speed and low power consumption circuit applications.
- *Sensors, detectors, LED, etc.*—TFTs of various structures and composing materials can be easily modified or connected to other devices to detect or generate changes of chemical, biological, optical, magnetic, radioactive, and other properties through controlling the transport of charge carriers, emission of photons, etc. The device can be embedded in solid, liquid, or gaseous environments. Although this area has been explored for many years, more new applications can still be discovered with the inclusion of nanodots or one-dimensional nanomaterials (*i.e.*, nanowires) in the structure.

Summary

The history of TFT development is as old as that of the modern MOSFET. In spite of early demonstrations of functional devices and products, the technology enjoyed great success only after the first report of a-Si:H TFTs prepared by the PECVD process. Fabrication of large-area TFT arrays on low temperature substrates has evolved with a high throughput but at low cost. In the past 20 years, there have been great advances in TFT device physics, material properties, and fabrication processes. The worldwide TFT LCD market has grown to about $110 billion in 2012. The current TFT application is mainly for pixel driving in large-area LCDs. The TFT architecture has also been used in products such as medical X-ray imagers and mobile consumer goods.

Industry R&D activities have been aiming at improving the cost, yield, and throughput of large-area panels. Academic research in many universities has helped in the understanding of material properties responsible for the TFT performance as well as the underlying chemistry and physics of the fabrication processes. At the same time, a large number of new applications in non-LCD areas have been reported.

Additionally, organic and oxide TFTs have been studied as possible alternatives for Si-based TFTs for lowering production costs or for improving carrier mobility. In the near future, advances in TFT technology will probably still be driven by the LCD industry. However, new TFT products in the areas of flexible electronics, integrated circuits, sensors, etc. may be realized once outstanding challenges are resolved. In summary, the TFT is a versatile solid state transistor configuration that can be applied to a wide range of products with few constraints on substrate size or material choice.

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Yue Kuo is the Dow Professor of Chemical Engineering, with a joint appointment in Electrical Engineering, Materials Science, and Engineering, at Texas A&M University, where he established the renowned Thin Film Nano & Microelectronics Research Laboratory in 1998. Previously, he spent two decades in industry R&D at IBM T. J. Watson Research Center and in Silicon Valley. His honors include Fellow of The Electrochemical Society, Fellow of IEEE, the ECS Electronics and Photonics Award, the Distinguished Research Achievement Award of Association of Former Students of Texas A&M University, IBM awards, honorary professorships, plenary/keynote/invited speeches, and numerous most-cited, downloaded, and highlighted papers. His two-volume TFT book is popular in universities and industry. His research has resulted in many world records and breakthroughs on TFTs and ULSICs with a broad impact on industry. He has served as an Associate Editor for ECS journals and is now the Technical Editor for the Technical Interest Area of Electronic and Photonic Devices and Systems for the *ECS Journal of Solid State Science and Technology* and *ECS Solid State Letters*. He received his Dr. Eng. Sci. from Columbia University. He may be reached at yuekuo@tamu.edu.

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