Study on semiconductor materials for TFT and their application in flat panel displays

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Abstract: TFT has been widely used in recent years because of its excellent performance. Considerable research has been done to meet the demand for high-quality and high-resolution displays, making the choice of well-suited and high-performance materials more significant than ever. This work first presents the overall development from a historic perspective. The next section introduces the basic structure of thin film transistors (TFTs), followed by recent advancements in semiconductor materials of TFT, including metal oxide, amorphous silicon, polycrystalline silicon, carbon nanotubes, and organic semiconductors. These materials are analyzed from various aspects: electrical properties, process temperature, fabrication complexity, mobility uniformity on large panels, and compatibility with substrates. After that, the properties of these materials are compared in terms of their large-scale fabrication capability in flat panel displays. Advantages and challenges are also discussed as each of the five materials is suitable for specific commercial products. This work provides a reference for the selection of TFT materials in future flat panel display industry.

Keywords: Semiconductor materials, thin-film transistors, flat panel displays, application.

1. Introduction

TFTs are considered the most significant technology for flexible electronics. It is widely used in flexible displays, wearable devices, and tactile skins due to its high performance as well as being lightweight, transparent, and stretchable at the same time.

Traditional metal oxide semiconductor field effect transistors (MOSFETs) concentrate on high mobility and process temperature. Complementary metal oxide semiconductor (CMOS) technology includes deposition, layered growth, and implantation, which involves high temperature (>1000˚C) and expensive processes but preserves the crystallinity and yields higher carrier mobility.

On the other hand, TFTs emphasize low-cost, large area, and low process temperature [1]. TFT technology grows device layers at <650˚C involving vacuum or solution deposition [2], allowing only amorphous layers to be formed with no limitation on the size and category of substrates [3].

In this review, the advancement of TFT materials is presented from a historical perspective. In the following section, dominant TFT materials are discussed in various aspects with emphasis on characteristic parameters and large area fabrication. Finally, specific applications of these materials in flat panel displays are analyzed.

2. Historical perspective

The first TFT was developed in 1962 with a wide-band-gap semiconductor cadmium sulfide. It was fabricated by evaporation of all components onto a glass substrate [2]. After that in 1964, photolithography was used to demonstrate the first metal oxide semiconductor (MOS) TFT with evaporated n-type SnO_2 on a glass substrate [2]. The main direction of applications for TFTs was revealed when TFT liquid crystal display (LCD) was developed in the 1970s [4]. However, due to its inferior charge carrier transport and instability in large surface fabrication, it was not until two decades later that TFT LCD began to commercialize. Major progress in stability and the characteristics of TFTs took place when hydrogenated amorphous silicon (a-Si:H) was introduced [5]. Because of its amorphous structure, a-Si:H has strong switching ability and bulk scale fabrication capability. Despite its low mobility, a-Si:H remains the dominant material for AMLCDs [1]. Later in

the 80s, greater mobility was achieved when polycrystalline silicon was introduced, but with problems of high process temperature and manufacturing cost. Soon after that, the fabrication temperature was reduced to 200˚C when a low temperature polycrystalline silicon (LTPS) method for n-channel TFTs was demonstrated in 1986 [6]. Almost at the same time, organic TFTs appeared with advantages of large area capability, low processing temperature, and manufacturing cost, but the issues of instability and inferior performance remain to be addressed. At the turn of the century, the development of innovative oxide semiconductors (for example ZnO, IGZO) further increased the charge mobility and lowered the power consumption of TFTs (Table 1).

Table1.Evolution of semiconductor materials [3]

Materials and devices	Year of development	Deposition techniques	Carrier mobility(cm^2/Vs)
CdS	1962	Evaporation	/
a-Si:H	1979	PECVD	1
LTPS	1980s	Deposition and laser annealing	500
Organic	1990s	Evaporation, coating	0.1-20
IGZO	2000s	sputtering	10-40

3. Semiconductor materials for TFT

3.1Basic structure

A thin film transistor is a 3-terminals field effect transistor made of conductive, dielectric, and semiconductive layers. Between the semiconductor layer that connects the source and drain electrodes and the gate electrode, there is a dielectric layer that allows the conduction of the charge carrier channel. There are four typical TFT structures depending on how the layers are positioned as shown in Fig.1. A TFT is staggered if the three electrodes are on the opposite side of the semiconductor, otherwise it is coplanar. Choices for fabrication of these four architectures rely on the deposition techniques, process temperatures or quantity of lithographic masks used [1]. The staggered bottom-gate structure is preferred when high temperature is required for the dielectric layer, whereas a coplanar top-gate is applied for high-temperature semiconductors.

The basic idea behind the working principles of TFTs is a voltage-controlled current source: the potential difference between gate and source electrodes induces a different level of charge accumulation at the semiconductor/dielectric interface, varying current through source and drain.

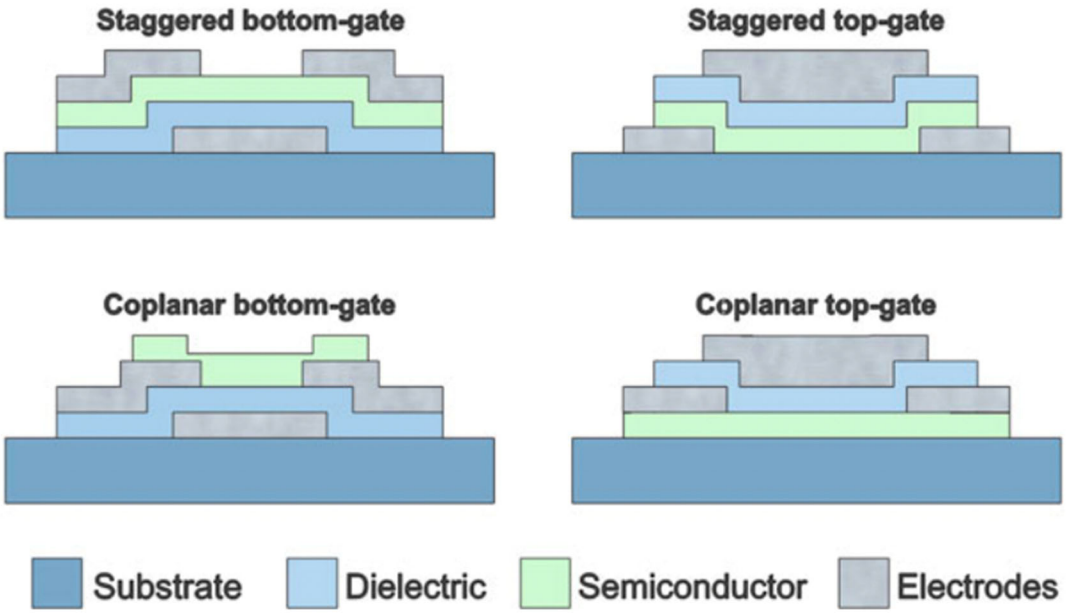


Figure 1. 4 most typical TFT structures [1]

3.2 Review of semiconductor materials

3.2.1 Metal oxide semiconductor (MOS) TFTs

Binary compounds such as SnO_2 and In_2O_3 were among the first MOS materials as channel-layer. After being introduced in 1964, MOS TFT has become the most significant TFT technology [2]. These binary materials have a wide band gap Eg>3eV and exhibit a high electrical conductivity even in the amorphous state [2,7]. This is due to the fact that spherical, widely-spaced, empty metal orbitals form the conduction band minimum [7]. Consequently, electron transport is easier through the overlap of the metal orbitals, which leads to a stronger degree of ionicity in the chemical bonding compared to covalent semiconductors like Si [8]. In the early 21st century, ZnO became the best-known binary metal oxide semiconductor. For example, R.L. Hoffman presented an ion beam sputtered ZnO channel. The channel was then subjected to a rapid thermal anneal (RTA) at a temperature of about 600 °C to improve the layer crystallinity and channel resistivity [9]. At the time ZnO-based TFTs have effective channel mobilities that range from 0.3 to 2.5 cm^2/Vs. In 2004, Elvira M.C. demonstrated that ZnO fabricated by radio frequency (RF) magnetron with a bottom gate configuration may be sputtered without impairing electrical characteristics (saturation mobility of $27cm^2/Vs$) at room temperature [10].

However, it has proved difficult to fabricate amorphous or single crystalline thin films out of most binary compounds. These compounds would lead to polycrystalline structures and grain boundary defects, which reduces the large area uniformity [11]. For this reason, multicomponent MOS arose as a new category of amorphous materials, such as IZO and IGO. By combining metal cations of various ionic charges and sizes, it is possible to create a stable amorphous phase in these multicomponent materials. Furthermore, adding a metal cation can help to stabilize and more precisely control the carrier density [2]. For example, Ga was first introduced into IZO in 2004 to form IGZO, which allowed μ_{FE} >>10 cm^2/Vs and therefore became one of the most popular semiconductor materials [2]. The amazing characteristics of oxide TFTs were then discovered through research, including high field effect mobility and large-area uniformity, as well as high compatibility with different fabrication techniques [2]. Alternatives to Ga doping in IZO have also been developed, as well as indium-free multicomponent metal oxide. For example, zinc tin oxide was introduced as channel material grown

via atomic layer deposition. Process temperature can be lower than 200˚C with adequate mobility (13cm^2/Vs) and a high on/off ratio (10^9-10^{10}) [3].

Generally, metal oxide semiconductors have better stability and mobility than a-Si:H, and superior large-scale uniformity than LTPS [12,13]. Table 2 compares the properties of TFT materials: a-Si, LTPS, IGZO, carbon nanotubes, and organic semiconductors. MOS presents higher electron carrier mobility than organic semiconductors with similar processing temperatures. Although its carrier mobility is lower than LTPS, it requires lower processing temperature and manufacturing cost, and presents larger scalability. Therefore, metal-oxide TFTs (mainly IGZO TFTs) are considered the most prominent ones for flexible electronics [12].

Table 2. Comparison between TFT materials based on important parameters.

TFT Material	a-Si	LTPS	IGZO	Carbon nanotube	Organic
Microstructure	Amorphous	Polycrystalline	Amorphous	Amorphous	Mainly polycrystalline
Mobility(cm^2/Vs)	0.1-1	50-100	10-30	>250 reported	0.1-10
Mobility uniformity	Good	poor	fair	Reported to be good	Poor/fair
Device type	NMOS	CMOS	NMOS	n/p type CMOS	n/p-type
Max. process temperature(˚C)	330	500	350	<300	250
Cost	low	high	low	Can be low	low

3.2.2 Hydrogenated amorphous silicon(a-Si:H)

Since a-Si:H was first introduced in 1979, it has become the most cost-effective among major categories of semiconductor materials. Around 1990, a-Si:H TFT allowed LCD to be commercially fabricated due to low fabrication temperature, and thus served as a driving element in both small and large-sized flexible displays [12,14].

A typical a-Si:H TFT has an on/off ratio over 10^6, a leakage current in the range of 10^{-12} A, and a threshold voltage of less than 3V. This implies instability under an extended period of gate bias stress, which restricts its applications in flexible devices [15]. Compared with similar traditional and commercialized materials, a-Si:H and LTPS are governed by similar physical principles, but a-Si:H TFT has better uniformity. However, due to low deposition temperature by PECVD, the mobility and reliability of a short-range order structure are significantly inferior to single-crystal silicon and LTPS devices [16].

3.2.3 Polycrystalline Silicon(poly-Si)

Poly-Si was first reported to have better stability than a-Si in 1984 [14]. Poly-Si films can be formed by varying degrees of crystallinity and mobilities using a-Si precursor films. However, new crystallization techniques were necessary to reduce the high process temperature. Years later, various methods have been developed, such as solid-phase crystallization (SPC), excimer-laser annealing (ELA), and sequential lateral solidification (SLS) [14]. The last two techniques are more established because the high density of intragrain defects from SPC restricts the characteristics [14].

As LTPS emerged in the late 1980s, fundamental advantages over metal oxides were demonstrated with its superior performance. The phenomenal mobility (up to 500 cm^2/Vs) makes it a stronger candidate in high resolution (8K UHD) display than all the other materials. Compared to metal oxides, LTPS had better long-term reliability and thermal conductivity (32W/mK). This prevents LTPS from self-induced thermal degradation which is a fatal issue for MOS with thermal conductivity of 1.4 W/mK [17].

One of the main challenges that LTPS has encountered is the compatibility with flexible substrates in the fabrication process. Plastics are considered the most compatible with LTPS due to their mechanical stability and low cost. Recent development has made progress on low temperature fabrication on plastic substrates. For example, LTPS fabricated on polyimide layers was reported by A.Pecora in 2007. The maximum process temperature was lower than 350˚C with good performance in mobility (up to 50 cm^2/Vs) [17]. However, one major issue is the incompatibility of thermal expansion between the substrate and the thin films, which leads to damage and cracking in the substrate [17].

3.2.4 Carbon nanotube

Continued downscaling of CMOS technology leads to the research of low-dimensional nanomaterials. The satisfying scaling capability and excellent transport characteristics are highly demanded for low-power dissipation and high-speed computing. One of the most prominent one-dimensional materials is single-walled carbon nanotube (SWCNT) with diameters ranging from 0.5-2.5 nm, and numerous SWCNTs comprise the channel layer of CNT-TFTs.

In 1998, single and multi-walled carbon nanotube TFTs were first presented by Martel R. et al, followed by deposition on flexible substrates six years later [12]. In the following years, great advancement has been achieved in improving the performance and uniformity of carbon nanotubes. For instance, a CNT TFT integrated circuit with flexible substrates was reported in 2008. The integrated circuits consisted of about 100 transistors and presented relatively high performance (mobility of 80 cm^2/Vs) [18].

There are multiple reasons why SWCNT can be a potential channel material: small geometric size, good thermal conductivity, relatively high mobility (up to 10 times higher than amorphous oxide), and low power dissipation. In addition, low process temperature of SWCNT makes it possible for deposition to be carried out on flexible substrates [12]. However, SWCNT devices have shown inadequate fabrication capability. Fabrication processes such as controlling large-area formation of SWCNT assemblies has proven to be difficult [12]. Recent progress has been made towards the hybridization of functional nanomaterials in the channel to overcome the issue of applying CNT only [12].

3.2.5 Organic

The first organic TFTs fabricated on a silicon substrate were demonstrated in 1986, with measured carrier mobilities of only 10^{-5} cm^2/Vs [12]. After that, a remarkable increase in mobility has been achieved as new organic material is applied. Until the turn of the century, carrier mobility has grown up to five orders of magnitude, with maximum mobility using vacuum deposited pentacene [19]. Currently, it has been demonstrated that the maximum on/off ratio can reach 10^6, with mobility ranging from 10 to 20 cm^2/Vs depending on the types of TFT [12]. Typical deposition methods are vacuum evaporation (higher mobility) and solution phase processing (large area). Solution-processed TFTs generally require room temperature which makes them low-cost [12].

Organic semiconductors allow relatively low process temperature (max.120˚C), various fabrication methods, and a high elastic modulus compatible with flexible substrates. In addition, both p and n types are available, enabling CMOS technology with lower power consumption. However, much lower carrier mobilities of OFETs limit high-speed applications. Moreover, they must be enclosed due to their vulnerability to environmental deterioration (caused by, for example, exposure to oxygen and UV light) [12].

4. Applications in flat panel displays

Flat panel display (FPD) is one of the biggest achievements made possible by the development of TFTs. Every FPD requires TFTs in the backplane to do pixel addressing. Only when a-Si TFTs were widely available did the development of FPDs take off [20]. After a 14-inch full-color LCD was demonstrated with a-Si TFTs in 1988, it was convinced that the cathode-ray tube would be ultimately replaced for television. However, as the size and resolution of FPDs continue to develop, new technologies are constantly needed to meet the demands [20].

4.1Basics of FPD

FPD consists of pixels with the electro-optical effect that can be switched for displaying an image. The electro-optical element in every pixel receives picture data from the active matrix addressing circuit comprised of at least one TFT. These TFTs hold data in a short addressing time until the subsequent refresh signal is received.

Two main types of technologies for FPD are liquid crystal display (LCD) and organic light-emitting diode (OLED). During charging of LCD, the electric field will be turned on and transmission of the ambient light will be altered by liquid crystal molecules. In the active-matrix OLED display, illumination can be modulated when an OLED is switched on by addressing TFT [20].

4.2 Materials for FPD

4.2.1 Amorphous silicon

About a decade after the introduction of a-Si:H, AMLCDs were made commercial and became the mainstream technology for high-resolution display. Because of its amorphous nature, a-Si has high mobility uniformity as well as low process complexity. In addition, it has the lowest cost and large-area scalability with adequate performance. However, its poor mobility (usually<1cm^2/Vs) is inadequate for the higher demand of refresh rates and larger panel sizes. The panel needs to be refreshed continually because too long a delay in refreshing the image would cause undesirable effects such as flicker or color shift. The electrical property also limits its applications in higher resolution displays since smaller pixels require further reduction in the dimensions of TFTs [21].

4.2.2 LTPS

LTPS is considered a replacement due to its better threshold voltage stability and mobility. Higher mobility increases display refresh rates and reduces the physical size and response time of TFTs. Moreover, LTPS is applicable for CMOS TFTs, which means various types of TFT channels are available for designers. For instance, PMOS is chosen for LTPS OLED because it is compatible with top-emission structures and allows lower process complexity compared to CMOS. Because a high PPI backplane cannot be achieved by other technologies, LTPS is by far the best technology that meets the demand for high resolution in today's mobile display where the flexible display has the largest market. Nevertheless, high process complexity (usually involves 5–11 photo masks) and high temperature (400–500˚C) are the main challenges to be overcome [20].

4.2.3 IGZO

Compared to LTPS, IGZO is not available for p-type TFTs and has less mobility (5-15cm^2/Vs). However, the amorphous nature means that IGZO has similar advantages as a-Si: good uniformity, low cost, and complexity. Source and drain metal contacts of IGZO can be directly patterned onto the channel layer, but LTPS and a-Si:H need the deposition of an additional doped contact layer sandwiched between the channel and metal contacts [21].

Besides, it is pointed out that maximum off-current leakage is one of the main factors determining the compatibility of a TFT with AMLCD applications [21]. Lower leakage is desirable because power dissipation is lower when a TFT is switched off, while high leakage current causes the cell to discharge. IGZO has an extremely low off-state drain current with a high on/off ratio being 10^9. The low leakage is the result of a wide-bandgap and unipolarity. A-Si:H and LTPS are both bipolar with

narrower bandgaps. Because of the reverse-biased operation, additional leakage through the gate insulator contributes to the recorded off current. IGZO has low gate insulator leakage because smooth surfaces of SiO_2, whereas LTPS grains result in pronounced roughness on the insulator-semiconductor interface. Low off-current, combined with a physically smaller size, makes it a winner for smartphones and tablets [9].

4.2.4 Carbon nanotube

SWCNT-TFTs have been demonstrated to be a very promising material for backplanes in flat panel displays. They have been reported to have high carrier mobility due to their perfect structure, as well as the ability to carry high current because of their high thermal conductance. Furthermore, the transparency and low fabrication temperature of CNT thin film make it compatible with flexible displays. Research has demonstrated the potential of CNT-TFTs on a laboratory scale. For example, Zou J. et al. demonstrated the first successful static and dynamic 6 x 6 pixels AMOLED displays driven by CNT-TFT. The device was reported to reach a maximum mobility of 45 cm^2/Vs and a current on/off ratio as high as 10^5 [20]. As larger area fabrication is demanded, printing technology based on SWCNTs has exhibited significant advantages. For example, a 20 x 20 printed SWCNT active-matrix backplane was reported to have even larger scalability. 97% of device yield was achieved with gravure printed backplane [22]. However, CNT-FETs have shown very limited fabrication capability since the discovery of carbon nanotubes. Although CNT films can be fabricated at low temperature and low cost, these two requirements limit the choices for production techniques to only a few, such as transfer techniques which results in nearly one-third of an SWCNT being metallic. This reduces the on/off ratio and requires further engineering of the geometries [20].

4.2.5 Organic

Flexible displays with plastic substrates have better capability to meet the multifunctional demand of FPDs, allowing great bendability and portability [23]. Flexible displays serve as an integrated system of a display element, a thin-film-transistor backplane, and a flexible substrate. All of them contribute to the overall mechanical flexibility and stability of the overall system.

Organic transistors are well suited for the backplane of flexible displays due to their high elasticity. Moreover, the low process temperature allows for extraordinary compatibility with plastic substrates. However, the instability in the mobility and threshold-voltage, as well as high-cost industrial fabrication device pose challenges from the point of large-scale production of a fully functional backplane unit [23].

5. Conclusions

Over the past decades, the advancement of electronic products in everyday life has proven that thin film transistors are crucial to the display industry and flexible electronics. This work discusses and summarizes recent progress for five major types of material: metal oxide, amorphous silicon, polycrystalline silicon, carbon nanotube, and organic semiconductors. A historical analysis of the evolution of TFT materials is given, and then different categories of material are compared concerning their characteristic parameters and large area fabrication. The choice of these materials defines their applications in flat panel display: while organic TFTs have better compatibility with flexible substrates, the other four types generally demonstrate higher performance. Although amorphous silicon TFTs still dominate the display industry, polycrystalline silicon and IGZO TFTs have been fabricated for the demand for higher resolution and larger panels, with IGZO TFTs having less manufacturing complexity. Besides, single-walled carbon nanotubes have been reported to include many advantages over the other materials, but challenges in fabrication techniques remain to be overcome before they reach large-scale production.

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