Thin Film Transistor - Basic Principles and Commercial Status

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Abstract: Thin Film Transistor, a semiconductor device, is now widely used in the field of displays, especially LCD. A correct understanding of the nature of various types of TFTs and their current situation in commercial market has a significant positive influence on obtaining the reliable prediction and economic benefits of the display industry or even other potential markets that have not received significant attention. The key characteristics of some representative TFT and their historical development process is introduced in this paper. Then the commercial application of TFT is discussed regarding display industry and other minor field. Finally, some possible future trends and relevant challenges are discussed.

Keywords: Thin Film Transistor, LCD, Sensor.

1. Introduction

As a branch of Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) family, the thin film transistor (TFT) invented in the middle of the last century and developed for over sixty years has become an indisputable key component in today's commercial display devices. From the small screen on the smart watch to the nearly 100-inch gigantic TV set, although TFT itself cannot be perceived by users directly, its existence is indispensable for the functional operation of these displays. Focused on the theme of TFT, this paper will first introduce the basic working principle and structure of general MOSFET, and then illustrate corresponding structure of four classic TFTs (Hydrogenated Amorphous Silicon TFT, Poly-Si TFT, Transparent Amorphous Oxide Semiconductor TFT and Organic TFT) respectively which are developed from MOSFET, as well as some of their characteristics compared with other types of TFTs. After that, this paper will point out some hallmark events of the emergence, development, and maturation (if exists) of different types of TFTs in a chronological order. Next, this paper would elucidate the application of various TFTs, with emphasis on its commercialization in the civil market. The content in this section would focus on LCD industry and other products that are related to distinguishing feature of TFTs. Finally, the paper would discuss about TFTs' future development trend and corresponding challenges. In short, the content of this paper explains the basic nature, historical development, commercial application, and future development direction of TFTs, which is conducive to researchers who are committed to entering the TFT field to have a preliminary understanding of fundamental awareness of this topic.

2. Structure and principle of TFT

2.1 General Structure and principle

Thin film transistor is a kind of MOSFET where thin film is deposited to form channel layer. Its basic working principle and architecture is close to those of MOSFET where the gate signal controls the activity of carriers in the channel, which results in turning on and off activities of the transistor. Though the basic principle of TFT is the same, there are also numerous different types of that, including poly-Si TFT, hydrogenated amorphous silicon TFT, transparent amorphous oxide semiconductor TFT, organic TFT and other categories.

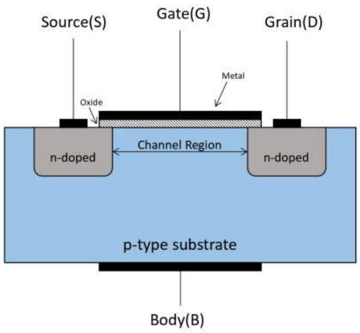

Figure 1. Cross-sectional structure of a NMOS

The basic structure is shown in figure 1, which also illustrates the working principle of general TFT. In a n-type MOSFET, two regions of Source and Drain are created by doping donor in the material of p-type substrate. The Gate terminal is connected to a piece of metal. Because of the existence of insulating oxide, there are almost no current passes through the gate all the time, so MOSFET is also called insulated gate FET or IGFET. When the gate voltage reach a specific value, the minority carriers in p-type substrate, which are the majority carriers of two n-doped region, assemble between source and drain region to form a conducting channel that allows the current to flow, and the value of this current is determined by the gate voltage, given a specified mosfet. The working principle mentioned above lays the foundation of TFT development. For a TFT, there is a thin film layer between source and drain that could produce carrier to create conducting channel according to the control voltage from the gate, and the substrate of TFT is usually changed to other materials,especially glass, rather than monocrystal silicon used in MOSFET.

2.2 Hydrogenated Amorphous Silicon TFT(a-Si:H TFT)

Figure. 2 demonstrates the cross-sectional area of the longitudinal structure of the Hydrogenated Amorphous Silicon TFT in inverted staggered structure manufactured by back-channel-etched(a) process and etch-stop process(b)respectively. The word inverted indicates that the channel is above the gate and the word staggered indicates that the source and drain do not share the same plane with conducting channel but they are on 2 different planes of the film.

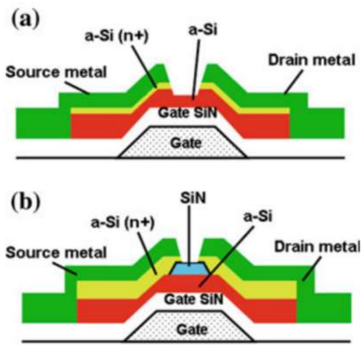

Figure 2. Cross-sectional structure of an a-Si:H TFT [1]

Although the structure described by these two words makes Hydrogenated Amorphous Silicon TFT seems to be strange and nonintuitive in architecture aspect compared with the conventional MOSFET mentioned above, it is actually the mainstream structure of Hydrogenated Amorphous Silicon TFT. This structure is the result of long-term development and optimization in semiconductor industry, which perfect the performance of a-Si:H TFT under many constraints including low temperature condition and large area substrates during manufacturing process. It is worth noting that, unlike MOSFET which contains both n-channel and p-channel types, till now only n-channel a-Si:H TFT has been commercialized, since p-channel a-Si:H TFT is not suitable for commercial applications for its limited performance [1].

2.3 Poly-Si TFT

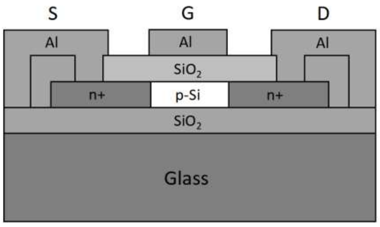

Figure 3. Cross-sectional structure of a poly-Si TFT

Figure 3 demonstrated a common structure of Poly-Si TFTs. Its structure is very similar to that of the silicon-on-insulator MOSFET, where a thin layer of silicon single crystal is covered on an insulator made of silicon dioxide or glass. One remarkable feature of Poly-Si TFT is that it reduct greatly of the cost and complexity during manufacturing.

Another characteristics of Poly-Si TFT is that it often requires a doping process named ion shower doping technology that implant phosphorus n-channel Poly-Si TFT and boron to p-channel Poly-Si TFT. This process is somewhat similar to the ion implantation technology for MOSFET, as a specified donor or acceptor with high concentration is injected in the transistor in both of the two technology [1]. To sum up, both the structure of Poly-Si TFT and its key processes in manufacturing are close to those of conventional MOSFET.

2.4 Transparent Amorphous Oxide Semiconductor TFT(AOS TFT)

Although its mobility is not very prominent compared with other materials, a-IGZO (amorphous indium gallium zinc oxide) containing InGaZnO4 is considered to be very suitable for AOS TFT research and application because of the importance of Ga for creating stable thin films. Figure 4 shows the structure of an inverted staggered Transparent Amorphous Oxide Semiconductor TFT with an etch stop layer [2].

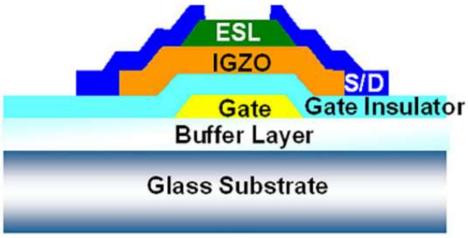

Figure 4. Cross-sectional structure of an a-IGZO TFT [2]

This configuration is more preferred now in AOS TFT, whereas original demonstration of a-IGZO TFT was both top-gated and coplanar like a common MOSFET. The preference of etch-stop process rather than back-channel etched process is a result of the vulnerability of back channel to the ambience. Experiments showed that the damage caused by etch-stop process on the back surface of TFTs is much smaller than that of back-channel etched process, and ultimately the performance of TFTs fabricated with etch-stop process is an order of magnitude better than that of TFTs fabricated with back-channel etched process[3]. A significant feature of amorphous oxide semiconductor is that it usually has greater conductivity and mobility than crystalline oxide ones, due to the different characteristics of ionic bonding in amorphous oxide semiconductor and covalent bonding in crystalline silicon semiconductor[4].

2.5 Organic TFT(OTFT)

Organic TFT utilizes the organic materials as channel layer. The drift motion of carriers in OTFT is achieved though the π-bonding orbitals in conjugated molecular organic materials[1]. There is no one standard structure that has been recognized to be best optimized for OTFT. Generally speaking, There are three classical structures for OTFT as shown in figure 5, figure 6 and figure 7 respectively [5].

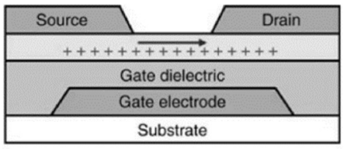

Figure 5. Bottom gate, top contact style

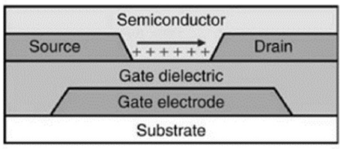

Figure 6. Bottom gate, bottom contact style

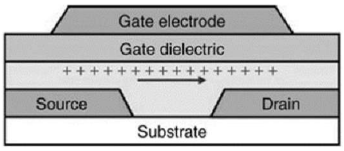

Figure 7. Top gate, bottom contact style

Unlike other TFTs mentioned before, OTFT manufacturing process usually does not contain doping technology. To form P-region and N-region in OTFT, the contact metal need to be carefully chosen so that its work function along with carrier bands in the semiconductor would result in expected P or N channel behavior at correct location in the architecture of OTFT[1]. Compared with TFTs made of inorganic materials, one key characteristics that OTFT possesses is its amazing compatibility with flexible substrate. This unique feature has inspired researchers to develop OTFT containing cheap substrates to realize both portable and foldable display devices.

3. History and development of TFTs

Since TFT belongs to a category of MOSFET, the early development history of TFT is also a part of the history of MOSFET. In 1957, John Wallmark invented a thin film MOSFET where the materials of gate dielectric was germanium oxide. In 1962, Paul K. Weimer, a colleague of John Wallmark in RCA laboratory in Princeton, New Jersey, developed the world's first TFT. The material in the channel of the very first TFT is a thin film made of polycrystalline CdS[6].

In 1979, P.G. Le Comber et al. manufactured the first hydrogenated amorphous silicon TFT. The gate dielectric layer of the TFT they invented was made of silicon nitride, as shown in Fig. 2. The remarkable advantage of a-Si:H TFT is that the manufacturing process is relatively simple and the stability of the device in the conventional environment is strong. The excellent properties of a-Si:H TFT laid the foundation for its future research and large-scale application in the field of AM LCD. Although a-Si:H TFT also has some disadvantages that can not be ignored, various reliable approaches have been proposed to solve its pertinent issues long ago[6].

Only shortly after researchers realized the value of hydrogenated amorphous silicon TFT in the field of AMLCD, another TFT that utilizes poly-crystalline silicon as gate dielectric material attracted people's attention. Long before the invention of TFT, poly crystalline silicon as a common high-temperature resistant material was widely used in the semiconductor industry, especially in the field of MOSFET devices and integrated circuits. At the result, the research on the properties of poly crystalline silicon materials has been reinforced in the academic and industrial circles. In the 1980s, poly-Si TFT were first manufactured and began to be directly applied to the AMLCD field. Although the mobility of a-Si:H TFT can meet some requirements, its mobility is still a huge limitation when it comes to fast switching circuit. Compared with the lower mobility of a-Si:H TFT which is usually below 1 cm2/Vs, the mobility of poly-Si TFT can be one to two orders of magnitude higher under specific process conditions[7]. The high carrier mobility of poly silicon TFTs has promoted the emergence and development of the second generation AMLCD. However, poly-Si TFT has not established supremacy over a-Si:H TFT in display market, as the performance of a-Si:H is still powerful. In brief, a-Si:H TFT is widely used in large-size diagonal AMLCD devices, while poly-Si TFT performs well in small-size diagonal AMLCD and AMOLED markets.

As for OTFT, its relevant principles first appeared in public in the 1960s, when the light emitting phenomenon of non crystalline organic materials driven by electricity was reported. In 1986, Tsumura et al. announced the invention of the first OFET, in which polythiophene polymer was used as the material of the film layer [8]. After many revisions and optimization of OFET since the 1980s, till now most OFETs are in TFT architecture, that is, most OFET devices can be called OTFT. By adopting the TFT structure, the material inside the OTFT is reduced. In the 1990s, when OTFT was initially applied to commercial market, the its carrier mobility of 0.1cm2/Vs was relatively small, which was lower than the mobility of 0.5~1.0 cm2/Vs of mainstream a-Si:H TFT in the same period. However, after 20-30 years of development, thanks to the continues researches and efforts in organic materials field, the mobility of OTFT has been several orders of magnitude higher than before, exceeding 10cm2/Vs . Compared with TFT made of inorganic materials, the significant advantages of OTFT is its reduced thickness, small weight, intense flexibility and low power consumption. In addition, polymers of organic substances are usually processed with solution, and the process used for deposition is just very suitable for forming thin films, which is also conducive to improving the performance of OTFT. However, OTFT also has some disadvantages that primarily caused by its organic materials. For instance, its lifespan is relatively short and vulnerability to water and oxygen undermine its reliability.

After entering the 21st century, the emerging transparent amorphous oxide semiconductor TFT, especially a-InGaZnO TFTs, have promoted another revolution in the field of LCD industry. In 2004, the article published by Kenji Nomura and others illustrated the idea of using transparent a-IGZO as the active channel material of TFTs. Compared with a-Si: H TFT and OTFT, a-IGZO TFT has higher mobility. Although poly Si TFTs may have even higher mobility, poly-Si TFTs do not have the advantage of transparency in general because their band gap is relatively small. Another strength of a-IGZO TFT, strong uniformity, also creates a potential for its further application in large diagonal AMOLED market where its rival poly-Si TFT is limited by its non-uniformity, although poly-Si TFT has already dominated small diagonal AMOLED market currently [9].

4. Current commercial status and application

4.1 Primary Applications of TFTs: LCD screen

One of the most crucial and extensive application of TFT family is LCD devices, in which a-Si:H TFT is the mainstream type that has been adopted for a long time till now. The small size and low power consumption of TFT enable each tiny pixel in LCD can be composed of individual TFTs, and this feature of LCD helps to achieve rapid refresh rate of the screen. In the early stage of its commercial application, TFT LCD was only primarily made as the screen of laptop computer. Its splendid performance from the market showed that the TFT LCD of laptop computer, as an important device that can provide human-machine interaction, has achieved great success in the upcoming internet era, and this success has driven the continuous upgrading of other relevant LCD devices, including desktop computer displays and large size televisions that are very common now. During the development of LCD in its commercial market, LCD manufacturers are committed to increasing the size of the glass substrate to produce more and larger TFT arrays on a single huge substrate, which not only reduces the manufacturing cost but also enhances the throughput of production [6]. At the same time, in order to adapt to the expanded substrate, each generation of TFT process have been upgraded to improve the performance of TFT and manufacturing speed, and some complex manufacturing processes have been reduced to less stages. The most direct manifestation of these optimization is the gradual improvement of the yield rate of TFT LCD in recent decades.

4.2 Other applications of TFTs

Although OTFT invented in the 1980s has several unique advantages over its inorganic counterparts, for example, its economical and high yield goal with superb compatibility of molecule structure tailoring and physical blending, the commercial application of OTFT is relatively less than that of a-Si:H TFT and AOS TFT, which are widely used in LCD devices. Till now, the first and possibly the only commercial product that applies OTFT technology is the flexible e-book display manufactured by a company named ‘plastic logic’. Figure 8 demonstrates a representative of their e-book display product, which incorporates OTFT active matrix with bi-stable electrophoretic display technology, and it obviously inherits the flexible nature of OTFT itself.

Figure 8. Flexible e-book display based on OTFT device by plastic logic

The application of AOS TFTs in display devices is far less than the a-Si:H TFT with matured technology and market, but they usually have higher mobility and larger leakage current, so now AOS TFTs are used as drivers for some circuits in OLEDs. Although the performance of AOS TFT is sensitive to external factors including humidity, ambient atmosphere and light, these problems can be solved by using appropriate process conditions, passivation layers and light blocking layers. In fact, the industry has already developed those approachew to attenuate congenital defects of AOS TFTs [10].

Most of the commercial applications of TFTs mentioned above are in the field of display devices. However, TFTs actually have many other commercial applications, which are mainly contributed by the special properties of different internal structures of various TFTs. For example, TFT can be applied to the equipment for detecting pH value, because the suspended gate dielectric structure will absorb hydrogen ions. Similarly, TFTs are also used in gas detection devices, since its semiconductor layers can absorb chemicals such as alcohols and N2O. In the field of biology and medicine, some protein or DNA analysis devices utilize TFTs as their core components, as the biomolecular adsorption process during the test will quantitatively affect the value of contact resistance. Another application of TFTs in the medical field is artificial retina, because of the changing photoconductivity on attached a-Si: H layer of TFT.

5. Future trends and challenges of TFT’s commercialization

5.1 LCD industry

Whether it is a mobile phone screen or a computer screen, most of the general public have to frequently use them nowadays. Since recently TFT LCD has gradually eliminated its rival CRT display’s share in the market, TFT LCD or OLED screens produced by LG, Innolux, Samsung and other famous manufacturers would still be the mainstream, and their current dominant position is unshakable at least in near future. Therefore, display will be the main field of TFT technology development. Although current TFT LCD products have fulfilled the demand of most users in terms of LCD performance, the fabrication cost of LCD can still be further reduced through technological innovation. This means that the TFT LCD industry is likely to continue the same development direction of the past decades, which is focusing on improving the yield rate and throughput.

The change from the demand side may also affect the development trend of TFT LCD. The 4K display gradually popularized in recent years is a possible point of growth. Though 4K displays only have a small share in the market today, the films and games that are constantly produced by the entertainment industry and the game industry with increasingly high requirements for electronic devices will inevitably raise the demand of some users for display equipment, which may prompt display enterprises to devote themselves to researching high-resolution TFT LCD with greater performance (including color, brightness, refresh rate or other indicators). However, considering the economic recession in many countries recently, such relatively expensive product may only occupy a very limited market, unless LCD manufacturers can masterly balance its performance and manufacturing cost.

5.2 Other possible trends

Although the previous commercial status of OTFT has nothing to do with success, the flexibility of OTFT create possibilities for it to be applied in wearable devices, automobiles, biological equipment, medical industry and other fields in the future. It is estimated by IDTechEx company that the total market for wearable devices in USA would be around 70 billion by 2026, which is quite considerable and attractive [10].

Compared with popular a-Si: H TFT, one feature of OTFT that might be ignored is that it has a lower leakage current of two or three orders of magnitude. The low leakage current can significantly improve the sensitivity of the sensor. Considering that OTFT itself has decent biocompatibility and is relatively easy to be miniaturized, OTFT may be applied to commercial bio-sensor field in the future. In fact, some sensors for biological active substance based on OTFT technology have already been developed, including deoxyribonucleic acid, protein sensors and other types [11]. Although these sensors have not been successfully commercialized, their market prospects are optimistic. For example, the important glucose sensors in medical devices are currently developing towards noninvasive types, and sensors based on OTFT can achieve this goal.

Nevertheless, several nonnegligible issues that limit the commercialization of OTFT ought to be tackled for its later application. First, the lack of material stack and standardized manufacturing process restricts the performance of OTFT, such as its stability and uniformity. Secondly, current manufacturers' vague balance between performance and cost of OTFT, along with their undefined target market has led to ambiguous and unpredictable result of OTFT development direction.

6. Conclusions

After clarifying the basic principle of TFT, this paper also introduces the characteristics and application status of four kinds of TFTs. A-Si: H TFT has a long history and mature technology with considerable share in the popular LCD display market, especially in large-size devices. Compared with a-Si: H TFT, poly-Si TFT has higher carrier mobility and is excellent in small-size AMLCD and AMOLED markets. OTFT possess amazing compatibility and flexibility, but its stability has always been a huge limitation so its commercial applications are relatively weak. The transparent amorphous oxide semiconductor TFT represented by a-InGaZnO TFT emerging after the 21st century has the advantages of both high mobility and transparency, but its performance in the display market is still not as good as matured a-Si: H TFT and poly Si TFT. The overall development trend of TFT will continue the previous direction, with the LCD business as the core driving force. However, the large-scale commercial application of OTFT specifically will be challenged by both technical difficulties and enterprise strategy. The above content covers the key parts of this article, which helps beginners in the field of TFTs to understand the respective properties of different classic TFTs and their current commercial applications.

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