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Introduction of Metal Oxide Thin Film Transistors

1.1 Progress of Thin Film Transistor Development

The concept of the field effect transistor (FET) was originally proposed in 1925 and patented in 1926, as shown in Figure 1.1 [1, 2]. The thin film transistor (TFT) is operated on the same principle as that of the metal oxide field effect transistor (MOSFET). The first functional TFT, which had an evaporated microcrystalline (mc) CdS semiconductor channel layer and SiO gate dielectric with a staggered structure, was reported by Weimer in 1962 [3]. It was originally designed for electronic circuit applications [4]. Subsequently, various types of inorganic or organic semiconductor materials including tin oxide were made into TFTs [5, 6]. Originally, TFTs were aimed at circuit applications. However, they could not compete with the silicon wafer-based MOSFETs. New applications of TFTs were searched based on the advantageous low-temperature, low-temperature process capability. Brody et al. [7] first reported a 6″ by 6″ active matrix liquid crystal display (AMLCD) with a CdSe TFT array. It opened the high-performance flat panel era because the TFT could provide gray-scale switching capability for LC in each pixel and a TFT array could be prepared at a low temperature on a large-area substrate.

In the beginning, there were many efforts in mass production of AMLCDs using TFT backplates, but only limited success was achieved due to many manufacturing issues. However, the report of the amorphous silicon (a-Si:H) TFT by LeComber et al. [8] in 1979 provided a viable solution in manufacturing the large-area AMLCDs. It immediately attracted great attention from all electronics companies. The intrinsic a-Si:H channel, n^+ ohmic contact layer, and gate dielectric in the TFT were all deposited by the plasma-enhanced chemical vapor deposition (PECVD) process. The low temperature process condition makes it possible to fabricate the large TFT

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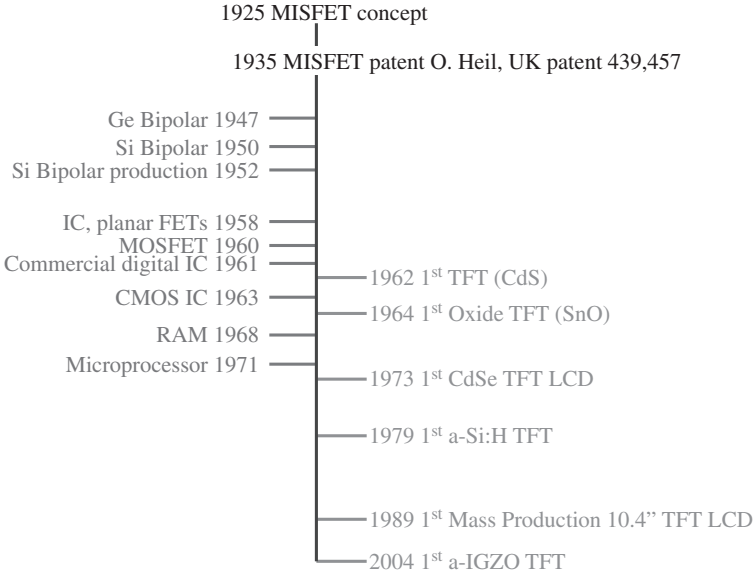


Figure 1.1 History of TFT and IC development. Source: Kuo et al. [1]/John Wiley & Sons.

array over a low-cost glass or even a plastic substrate. The gate dielectric and channel layers can be deposited by one-pump-down, which warrants the high performance and reliability of the TFT. The 10.4″ direct-view TFT LCD was included in the IBM ThinkPad PC in 1989. Other a-Si:H TFT-based products, such as X-ray medical imagers, gas, pH, photo, and magnetic sensors, were published in the literature [9]. Commercial 98″ TFT LCD TVs were available on the market in 2023 [10]. Glass substrates as large as 3 m by 3 m have been used in the 10.5th generation production equipment. The TFT LCD industry became the second largest electronic industry after the IC industry.

The main disadvantage of the a-Si:H TFT is the low field effect mobility (μ_{eff}), i.e., typically less than 1 cm^2/V s. which limits its applications in high-speed or high driving-current products, such as the display driver circuit or the organic light-emitting diode (OLED). On the other hand, the polycrystalline silicon (poly-Si) thin film has been used as the gate electrode in MOSFETs since 1970s. It is natural for researchers to develop poly-Si TFTs from the early stage. The poly-Si TFT can have a mobility 2 orders of magnitude higher than that of the a-Si:H [11]. However, it is difficult to mass-produce poly-Si TFT arrays on a large-area substrate at a low temperature due to manufacturing reasons. The high-mobility poly-Si TFT is commonly made of high-temperature deposited poly-Si

film or thermally annealed a-Si film, which is incompatible with the thermal stability of commercial display glass. The low thermal-budget laser annealing method, which provides the best poly-Si characteristics, suffers from low throughput. Therefore, currently, most poly-Si TFTs are used in small-sized displays.

Despite the early report of the high mobility SnO_2 TFT, i.e., $\mu_{eff} = 70\,cm^2/V\,s$, in 1964 [6], the metal oxide TFT was never used in commercial products until the report of the amorphous indium gallium zinc oxide (a-IGZO) TFT by the Hosono's group in 2004 [12]. The renewed interest in industry and academia came from the possibility of mass production of the high μ_{eff} at a low temperature over a large-area substrate. The original a-IGZO TFT was made of the pulsed laser ablation deposition method at room temperature. The original large off-current (I_{off}) was later reduced to $<10^{-14}$ A [13]. Also, the complete TFT could be fabricated by the sputtering or PECVD process, which is suitable for the large-area, low-temperature, and high-throughput production requirements.

1.2 Progress of Metal Oxide Thin Film Transistor Development

Figure 1.2 shows a short summary of some important events related to metal oxide TFTs. For the rest of this book, the term "metal oxide TFT" will be shortened as "oxide TFT." Shockley and Pearson first reported that the p-type semiconductor Cu_2O could be used as a channel material for the FET 1948 [14]. The result remained at the current field modulation level and almost unchanged to date. Although several Cu^+-based p-type oxide semiconductors, such as $CuAlO_2$, have been reported, no good performance TFT has been reported so far [15]. In 1954, semiconducting oxide glasses based on V_2O_x-P_2O_5 were reported by a group at Sheffield University [16]. This is the first report on the electronic conducting (bulk) glass, but the conduction is due to variable-range hopping between localized V^{4+} and V^{5+}. Thus, this type of oxide semiconductor has very small mobility and cannot be used as the TFT channel material. Since then, it is well-known that transition metal oxides exhibit semiconducting properties. Transition metal cations have an open shell structure in their d-orbitals and give visible absorption originating from a d-d transition. Since these vacant d-levels give a large density of states (DOS) in the gap, it is hard to shift Fermi level (E_F) significantly exceeding these DOS. This is the reason why transition metal oxide semiconductors do not work as TFT channel materials. Requirements on TFT channel semiconductor materials are much more severe than those for p-n junction formation because the E_F has to shift to beyond the valence

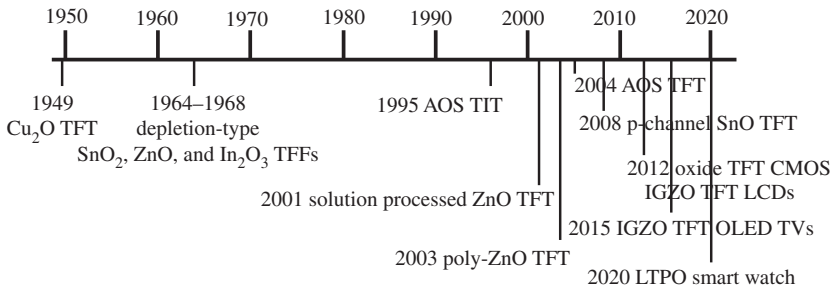


Figure 1.2 Examples of important events related to metal oxide TFTs.

band maximum (VBM) or the conduction band minimum (CBM) upon the application of a gate voltage. High sensitivity of Cu^{+} to oxidation to Cu^{2+} at the surface and grain boundary [17] prevents the gate-bias-induced band conduction notwithstanding Cu_2O thin films have high Hall mobility of $\sim 90\,cm^2/V\,s$ [17].

Since the first report of the SnO_2 TFT by Klasens and Koelmans at Philips Research Laboratories in 1964 [6], there have been many studies on oxide TFTs. In 1972, a study of the optical and electrical properties of Cd_2SnO_4 revealed its semiconductor properties [18]. In 1996, Hosono et al. [19] described the electrical properties of three transparent conducting amorphous oxides: a-$AgSbO_3$, Cd_2GeO_4, and Cd_2PbO_4 having an electron mobility of $\sim 10\,cm^2/V\,s$. This discovery was followed by the report on crystalline transparent oxide semiconductors [20] and by the report on the room-temperature fabrication of transparent flexible TFTs using amorphous oxide semiconductors [12]. In 2003, Hoffman et al. [21] reported on the ZnO-based transparent thin-film transistor.

Oxide TFT research was revisited extensively by several groups since 2000. A motivation was to develop TFTs with higher mobility and facile fabricability for next-generation flat panel displays (FPDs), such as OLEDs. Among them, noteworthy is a paper in 2001 by Ohya et al., which is the first report of a non-vacuum, solution process in preparing ZnO-TFTs, i.e., drop-coating of $Zn(CH_3COO)_2$ solution and subsequent heating in air [22]. Since high chemical stability in an ambient atmosphere is one of the material advantages of oxide semiconductors, this approach utilizing this intrinsic nature of oxides became a milestone in the fabrication of solution-derived oxide TFTs. Many papers on ZnO-TFTs deposited by sputtering or pulsed laser deposition were reported but serious issues, such as poor reproducibility and large hysteresis, arising mainly from the complex grain boundary nature, were pointed out. The design concept of transparent amorphous oxide semiconductors (TAOS) with large electron

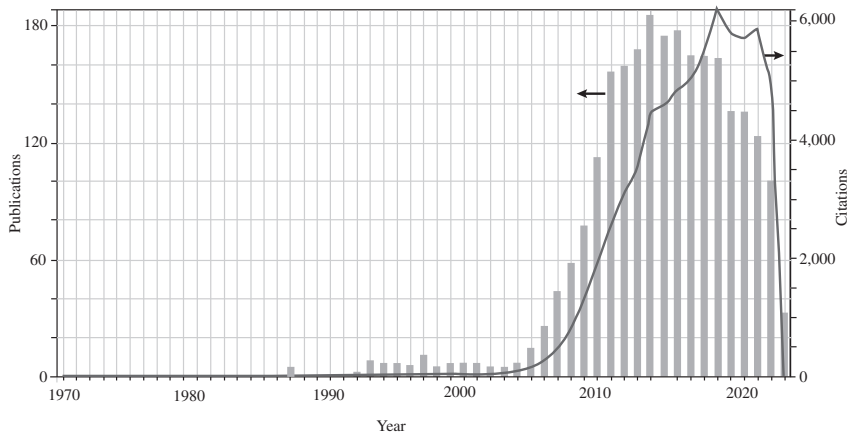


Figure 1.3 Number and citation of publication with title containing "oxide" and "thin film transistors". Source: Data were taken from Web of Science.

mobility was proposed by Hosono et al. [23] in 1996 along with several demonstrative materials. Although amorphous InO_x had large electron mobility and high transparency, the performance of a-InO_x TFTs was insufficient due to high carrier concentration [24]. A TAOS material, i.e., IGZO, appropriate for TFTs was found [12]. First, IGZO TFT was fabricated using epitaxial thin films of IGZO in 2003, exhibiting excellent performance, mobility of ~80 $cm^2/V\,s$ and on- and off-current ratio (I_{on}/I_{off}) of 10^6 [25]. Subsequently, amorphous IGZO TFT fabricated on plastic substrates with mobility of ~8 $cm^2/V\,s$ was reported [12].

Figure 1.3 shows the number of SCI journal papers with titles containing "oxide thin film transistor" and their citations from 1970 to 2023. The number of oxide TFT papers and their citation started to boost in 2004. This distinct trend suggests these two papers triggered much attention of TFT researchers to oxide semiconductors and this excitement, primarily on IGZO, has continued to date. Many monographs and review papers on oxide TFTs have been published [13, 15, 26–52].

1.3 Layout of Book Chapters

The arrangement of chapters follows the concept of materials, devices, processes, and applications.

- Chapter 2 discusses fundamental electronic properties and material properties of oxide semiconductors. The emphasis is on issues related to the material requirement in preparing high-performance oxide TFTs.

- Chapter 3 discusses device physics and the design of oxide TFTs. Special issues on modeling, tera-hertz operation, and reliability of oxide TFTs are analyzed in this chapter.
- Chapter 4 describes the oxide TFT fabrication processes considering the large-area thin film deposition methods and transistor structures. There is additional emphasis on the fabrication of emerging flexible oxide TFTs and solution-based processing methods.
- Chapter 5 reviews oxide TFT applications. In addition to principal requirements, actual examples of applications on various types of flat panel displays, sensors, imagers, and circuits as well as flexible electronics are given and discussed.

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