2.1 Brief History of TFTs

The thin-film transistor (TFT) and its potential can be traced back to the 1930s when the invention of the TFT was patented and the basic principle is known today as the metal-semiconductor field-effect transistor. Later on, insulating materials (such as aluminum oxide) was introduced between the semiconductor (copper sulfide) and the field-effect electrode (aluminum), forming the so-called metal-insulator-semiconductor field-effect transistor (MISFET) [Srivastav (2009)].

In 1962, RCA laboratories reported the fabrication of a TFT using thin films of polycrystalline cadmium sulfide (CdS) as the semiconductor material. Since the mid-1980s, silicon-based TFTs have become the most important device for active-matrix liquid crystal displays (AMLCDs). In the past ten years, amorphous silicon (a-Si:H) TFTs have successfully dominated the large-area LCD product market. Meanwhile, research and development activities on polycrystalline silicon (poly-Si) TFTs are steadily increasing [Weimer (1962); Voutsas (2003)]. Recently, a new generation of oxide semiconductors are being studied and applied as the active material to the TFT device, particularly the zinc oxide (ZnO) and InGaZnO (IGZO) thin films.

The primary study of the flexibility of TFTs starts in 1994, when a-Si:H TFT circuits were fabricated on flexible polyamide substrates and subsequently formed on flexible stainless steel in 1996. In 1997, polycrystalline silicon (poly-Si) TFTs were made on plastic substrates using a laser annealing method. Thereafter, widespread research has been carried out on flexible electronics and remarkable progress has been achieved in the utilization of flexible displays on either steel or plastic foil substrates [Theiss (1996); Yang et al. (1997)].
2.2 Review of literature

In the study of the performance of thin film transistor design, the literature based on the material type or structure of the reported thin films transistors have been reviewed. This chapter provides the details of the literature studies.

2.2.1 Review of progress in a-Si:H material TFTs

Chen et al. (1996) reported fabricated a-Si:H TFT by high deposition rate PECVD method. The highest mobility 1.47 cm²/V.s was reported with this material but the fabrication cost was high because of the plasma etched chemical vapor deposition method. Lim et al. (2000) used another deposition method and achieved a field effect mobility of 1.37 cm²/V.s at comparatively low cost by plasma treated silicon nitride. Wong et al. (2003) reported the array of a-Si:H TFT fabricated and achieved the higher switching characteristics $I_{ON}/I_{OFF}$ of order of $10^8$. Sazonov et al. (2005) fabricated a-Si:H TFT on a plastic substrate at a very low cost, but with the limitation of a low field effect mobility of 0.8 cm²/V.s.

2.2.2 Review of progress in poly-Si and Si material TFTs

Pangal et al. (2001) fabricated polysilicon TFTs and observed a channel mobility of 15 cm²/V.s with a compromised $I_{ON}/I_{OFF}$ ratio of the order of $10^5$. Guo et al. (2008) in their paper have shown that the switching $I_{ON}/I_{OFF}$ limitation can be improved by an ultrathin channel device structure and reported the relation of $I_{ON}/I_{OFF}$ ratio with channel thickness. $I_{ON}/I_{OFF}$ obtained by them was of order of $10^{11}$. Zhenqing et al. (2011) fabricated SiC
NWFET and have shown advantage in stability of the device, but with a compromise in mobility 13.4 cm\(^2\)/V.s. They reported the achievement of a device that can withstand high power due to the use of SiC nanowire. Similarly Tsong et al. (2012) in a paper, shown that the integration of SiO\(_2\) into Poly-Si TFTs leads to a low subthreshold swing of order of 2-2.5 cm\(^2\)/V.s, making it useful for memory and SOP technology. Another paper by Jiang et al. (2012) reported a SiO\(_2\) gated TFT with less mobility, but ultra-low voltage operation (\(V_{TH} = 0.19\)V), making it useful in transparent flexible electronics applications.

### 2.2.3 Review of progress in Zinc Oxide TFTs

Hoffman et al. (2003) introduced a ZnO TFT with low mobility and explained its use for AMLCD display application. Fortunato et al. (2003) proposed TFT based on ZnO at room temperature that reported a high mobility of order 70 cm\(^2\)/V.s but the reduced \(I_{ON}/I_{OFF}\) ratio was reported. They fabricated ZnO-TFT with room temperature processing, making it very promising for the next generation of invisible and flexible electronics.

High mobility could be achieved, but they reported a reduction in \(I_{ON}/I_{OFF}\). Chung et al (2014) have fabricated complementary MOS TFT with a p-MOS of SnO material and an n-MOS with ZnO. Although low mobility was obtained but they recommended the potential of the device in large area applications. They reported that ZnO material is a transparent in the visible region of the spectra and it is less light sensitive. Besides, this primary advantage of transistors using ZnO as active channel layer, is the high electron channel mobility and the corresponding higher drive current with faster operating speeds. Another predominant advantage of ZnO is its deposition at or near room temperature as a high-quality polycrystalline structure, which makes it suitable for the use in flexible substrates.
2.2.4 Review of progress in InGaZnO (IGZO) material TFTs

InGaZnO (IGZO) is currently emerging as the preferred semiconductor for high performance and transparent large-area electronics. The advantage of IGZO material is its amorphous state compared to polycrystalline ZnO. The disorder in the IGZO system is comparable to a-Si:H thin films, providing excellent electrical uniformity over large areas compared to polycrystalline materials while possessing higher field effect mobilities. Park et al. (2008) reported a TFT based on IGZO with a mobility of 13.5 cm²/V.s. Gwanghyeon et al. (2011) fabricated a dual gate coplanar IGZO TFT and reported a higher mobility of 15.1 cm²/V.s and a higher on-off ratio, but with the limitation of an increase in the subthreshold slope. Ming et al. (2012) in their paper on IGZO TFT have shown results in mobility of 18.5 cm²/V.s and a very low threshold voltage, making it suitable for ultralow voltage flexible displays. Hsu et al. (2013) reported an improved IGZO TFT mobility of 76 cm²/V.s, and the I_{ON}/I_{OFF} ratio was 10^5. IGZO TFT mediated by silver nanowire was proposed to achieve higher on-off ratios for transparent flexible large area applications. In another research in IGZO TFT was fabricated using gate dielectrics such as Ta_2O_5 (tantalum pentoxide) and La_2O_3 that has improved mobility and I_{ON}/I_{OFF} at low threshold voltage.

Currently, transparent electronics are one of the most advanced topics for a wide range of device applications, including invisible electronic circuitry, next generation displays, and optoelectronic devices. The key components of transparent electronics are transparent conductive oxides (TCOs). TCOs are a special class of materials which possesses both high visual transparency due to their large band gap energy and high electrical conductivity. One commonly used TCOs is ZnO, and the birth of transparent electronics is normally associated with the reports on ZnO TFTs presented in 2001-2003. In addition to electrical parameters there has been interest of researchers in finding fabrication methods to improve electrical behavior. A few of the findings and reported literature are discussed in the subsequent section.
Biing et al. (1992) proposed a type of amorphous silicon (a-Si) thin film transistor (TFT) in which a depletion gate is added to the top of the second nitride layer of a conventional a-Si TFT. In such a transistor, switching is done by the depletion gate instead of the accumulation gate as in conventional a-Si TFT's. The transistor exhibited a comparatively high ON-OFF current ratio, low contact resistance, and low gate-source capacitance. It was revealed that it is possible to fabricate TFT LCDs that have very small voltage jumps across the liquid crystal capacitor. The use of DGTFT improved the switching speed of a-Si integrated circuits.

Jacobs et al. (1997) have explored the behavior of indium implanted in Silicon-On-Insulator (SOI) material by using SIMS analysis to obtain the doping concentration profile as a function of the silicon film thickness for a fixed implant depth, and as a function of the implant depth for a fixed silicon film thickness. Based on the experimental data, it has been observed that indium can be highly mobile and can diffuse throughout the buried oxide. A lower temperature process is necessary to maintain the indium profile in thin-film SOI transistors.

Zhonghe et al. (1998) have shown the use of aluminum oxide as the gate insulator for low temperature polycrystalline SiGe thin-film transistors. The composition of the deposited aluminum oxide was found to be almost stoichiometric (i.e., Al$_2$O$_3$), with a very small fraction of nitrogen incorporation. Good TFT performance has been reported on devices with 50-nm thick Al$_2$O$_3$ gate dielectric layers. A field effect mobility of 47 cm$^2$/V.s, a threshold voltage of 3 V, a subthreshold slope of 0.44 V/decade, and an on-off ratio above $3 \times 10^5$ at a drain voltage of 0.1 V could be obtained. Their results indicated that the direct interface between the Al$_2$O$_3$ and the SiGe channel layer was sufficiently passivated to make Al$_2$O$_3$ a better alternative to grown or deposited SiO$_2$ for SiGe field effect devices.

Fortunato et al. (2004) in his paper presented the results of thin film transistors produced completely at room temperature using ZnO as the active channel and silicon oxynitride as the gate dielectric. ZnO-based thin film transistors (ZnO-TFT) present an average optical transmission (including the glass substrate) of 84% in the visible part of the spectrum. The reported ZnO-TFT operates in the enhancement mode with a threshold voltage of 1.8 V.
They reported the field effect mobility of 70 cm²/V.s, a gate voltage swing of 0.68 V/decade and an on-off ratio of 5 × 10⁵.

Teresa et al. (2006) used pentacene for organic thin-film transistors (OTFTs) which was deposited on the SiOC film by thermal evaporation. The transfer characteristic of the pentacene channel as the active layer is dependent on the chemical properties of a surface on gate insulator. Hybrid type SiOC film can have all chemical properties from organic to inorganic properties according to the deposition condition. Pentacene on SiOC film shows the gradient or normal growth because of the C = C bond in SiOC film.

Gwanghyeon et al. (2011) proposed the fabrication of a DG coplanar homojunction a-IGZO TFT. The electrical characteristics and stability of dual–gate (DG) coplanar homojunction amorphous indium–gallium–zinc–oxide thin-film transistors (a-IGZO TFTs) on glass substrates are described. The DG a-IGZO TFT demonstrated excellent electrical performance with sub threshold swing of 99 mV/decade, field-effect mobility of 15.1 cm²/V·s, and on-off current ratio of 10⁹. By applying various bias voltages on the TFT gate electrode, it is found that the TFT threshold voltage can be controlled without any change of the subthreshold swing and off current and recommended the TFT as a strong candidate for AM-OLED pixel circuits.

Shieh et al. (2011) developed a zinc oxide (ZnO) thin-film transistor (TFT) by using the sol-gel method with spin coating. The I-V characteristics of the ZnO thin film transistor showed a high ION/IOFF ratio up to ~ 10⁶. It was reported that the resistances of a ZnO TFT device will affect many characteristics, such as threshold voltage, mobility, on-off current ratio, sub-threshold swing, and so forth.

Ming et al. (2012) proposed a high-performance amorphous InGaZnO (a-IGZO) thin-film transistors (TFT) fabricated on a colorless polyamide substrate using a top-gate self-aligned structure. All thin films are deposited by roll-to-roll-compatible sputtering processes at room temperature. The maximum field effect mobility 18 cm²/V·s, threshold voltage 1.35V, subthreshold slope 0.1 V/decade, and the on/off current ratio of about 10⁵ were obtained. The results highlighted that excellent device performance can be realized
in a-IGZO TFTs without compromising manufacturability. It was reported that the device is suitable for active devices in large area and low cost flexible electronics and display applications.

Rongsheng et al. (2012) designed and fabricated n-type GaN thin-film transistors (TFTs) based on AlN/GaN heterostructures. GaN and AlN thin films were sequentially deposited by reactive dc magnetron sputtering at room temperature on quartz. The proposed GaN TFTs exhibited good electrical performance such as field mobility of 2.5 cm²/V·s, a threshold voltage of 2.4 V, on-off current ratio of $1.2 \times 10^5$, and a subthreshold swing of 0.5 V/decade. The proposed GaN TFT has great potential in the application of next-generation flat-panel displays.

Han et al. (2012) investigated and characterized the photo-generation properties in an amorphous SiGe:H thin film transistor (TFT) by analyzing the electrical performance under illumination. The a-SiGe:H TFT showed a higher photo sensitivity at wavelengths in the IR regime, and as the SiGe:H layer was thicker, the generated photo current proportionally increased due to the higher photon absorption. In particular, it was observed that regions under the source-drain electrode played a critical role in generating the photo currents, which was demonstrated by technology computer aided design simulation.

Sang et al. (2012) reported the effects of monochromatic illumination on the electrical performance of a-SiGe:H thin-film transistor (TFT) and explained the use of this device in infrared (IR) image sensing touch displays. When the photo response was observed in a real liquid crystal display (LCD) operation environment, they showed the display contents dependence, meaning that the supply of external IR light source for the touch sensing was effectively independent of any ambient light condition. Additionally, the optical noise from the display operation was eliminated using the block operation as well as the backlight IR light-emitting diode (LED) light modulation. With the device, clear touch images were obtained in the a-SiGe:H photo sensor embedded LCD panel.
Rongsheng et al. (2013) fabricated GaN thin films utilized as an active channel layer to produce bottom gate n-type thin-film transistors (TFTs). The GaN thin films structure were deposited by reactive dc magnetron sputtering using a liquid gallium target. The resulting GaN TFTs exhibited good electrical performance, including a field-effect mobility of 5 cm²/V.s, a threshold voltage of 11.5 V, an on-off current ratio of $6 \times 10^6$, and a subthreshold swing of 0.4 V/decade. The reported GaN TFTs has great potential in flat-panel display application.

Hsuanhsu et al. (2013) demonstrated the feasibility of a full room temperature InGaZnO thin-film transistor (TFT) using trilayer gate dielectric on flexible substrate. Through integrating a high-$\kappa$ SiO$_2$/TiO$_2$/SiO$_2$ (STS) gate-stack, as well as InGaZnO channel thickness modulation, the resulting flexible indium–gallium–zinc oxide (IGZO)/STS TFTs showed a low threshold voltage of 0.5 V, a small subthreshold swing of 0.129 V/decade, a high field effect mobility of 76 cm²/V.s, and a good $I_{ON}/I_{OFF}$ ratio of $6.7 \times 10^5$, which had the potential of its application in high-resolution flexible displays. Normal growth of pentacene molecules increased the grain size of the surface of the pentacene on SiOC film, and the mobility of OTFTs on SiOC films.

Qian et al. (2014) conducted a comparative study of amorphous InGaZnO thin-film transistors with Ta$_2$O$_5$ and TaLaO gate dielectrics. It was found that the electrical characteristics of thin-film transistors, including saturation carrier mobility, subthreshold swing, hysteresis, and on-off current ratio, can be effectively improved by the incorporation of La in Ta$_2$O$_5$ gate dielectric. The results demonstrated the potential use of TaLaO gate dielectric for making high-performance a-IGZO TFTs used in the field of high-speed high-resolution FPDs.

Minami et al. (2005) presented the status and prospects for further development of polycrystalline or amorphous transparent conducting oxide (TCO) semiconductors used for practical thin-film transparent electrode applications. The important TCO semiconductors are impurity doped ZnO, In$_2$O$_3$ and SnO$_2$ as well as multicomponent oxides consisting of combinations of ZnO, In$_2$O$_3$ and SnO$_2$. They showed that the need for transparent electrodes for optoelectronic device applications is the availability of indium-
tin-oxide (ITO). The main constituent, indium, is a very expensive and scarce material. Al- and Ga-doped ZnO (AZO and GZO) semiconductors are promising as an alternative to ITO for thin-film transparent electrode applications.

Hosono et al. (2007), reviewed research progresses made in transparent conductive oxide (TCO) materials and electronic and optoelectronic devices based on these materials. First, they described the materials including p-type materials, TCO (β-Ga₂O₃), epitaxially grown ITO, transparent electrochromic oxide (NbO₂F), amorphous TCOs, and nano porous semiconductor 12CaO·7Al₂O₃. Second, they presented TCO-based electronic/optoelectronic devices realized till date. Finally, optoelectronic properties originating from 2D-electronic nature in p-type layered oxychalcogenides were proposed.

Noh et al. (2010) fabricated thin-film transistors (TFTs) using an indium oxide (In₂O₃) thin film as the n-channel active layer by RF sputtering at room temperature. The TFTs showed a thickness-dependent performance in the range of 48–8 nm, which is described in terms of the total carrier number in the active layer. Optimum device performance at 8-nm-thick In₂O₃ TFTs had a field-effect mobility of 15.3 cm²/V.s, a threshold voltage of 3.1 V, an I₉/I₀ ratio of 2.2 × 10⁸, a subthreshold gate voltage swing of 0.25 V/decade. These results suggested that sputter-deposited In₂O₃ is a promising candidate for high-performance TFTs for transparent and flexible electronics.

Fortunato et al. (2007) in a paper, presented the results of thin film transistors produced completely at room temperature using ZnO as the active channel and silicon oxynitride as the gate dielectric. The ZnO-based thin film transistors showed an average optical transmission of 84% in the visible part of the spectrum, and a threshold voltage of 1.8 V. A field effect mobility of 70 cm²/V.s, a gate voltage swing of 0.68 V/decade and an on-off ratio of 5 × 10⁵ was reported by them. They confirmed the ZnO TFT as a very promising for the next generation of invisible and flexible electronics application.

Ahn et al. (2014) showed the effect of hafnium addition in the electrical performance and bias stability of ZnO based thin-film transistors (TFTs). All channel layers were deposited by atomic layer deposition. Multilayer oxide channel TFTs consisting of two or three Hf-
doped ZnO (HZO) and ZnO layers were developed for the realization of adequate channel mobility and electrical stability. They reported improved subthreshold swing and bias stability by the deposition of the thin-HZO layers with amorphous phase as the first and final channel layers. The use of a conductive ZnO layer enhanced the device mobility. The origin of the stability issues and channel design was explained by them on the basis of the electrical performance of various TFT structures.

Park et al. (2009) proposed transparent ZnO thin-film transistors (TFTs) with a defect controlled channel and channel-dielectric interface to maintain good photo stability during device operation. They presented a cross-sectional view of a top gate ZnO based transparent TFT, storage capacitor cell structure connected to front panel organic light emitting diode pixels to operate in bottom emission mode.

Lopes et al. (2009) in a quantitative study of the dynamics of threshold voltage shifts with time in gallium-indium zinc oxide amorphous thin-film transistors, presented a standard analysis based on stretched exponential relaxation. For devices using thermal silicon oxide as gate dielectric, the relaxation time is $3 \times 10^5$ s at room temperature with activation energy of 0.68 eV was reported. The threshold voltage shift became faster after water vapor exposure, suggested that the origin of this instability is charge trapping at residual water related trap sites.

Jeong et al. (2008) investigated the impact of the passivation layer on the stability of indium-gallium-zinc oxide (IGZO) thin film transistors. While the device without any passivation layer showed a huge threshold voltage ($V_{TH}$) shift under positive gate voltage stress, the suitably passivated device did not exhibit any $V_{TH}$ shift. Instead, the $V_{TH}$ instability was attributed to the interaction between the exposed IGZO backsurface and oxygen and/or water in the ambient atmosphere during gate voltage stress.

Nomura et al. (2004) predicted that transparent electronic devices formed on flexible substrates would meet emerging technological demands, where silicon-based electronics cannot provide a solution e.g. active flexible applications including paper displays and wearable computers. However, the performance of these devices has been reported
insufficient for use in practical computers and current-driven organic light emitting diode displays. It was reported that fabricating high-performance devices is challenging, owing to a trade-off between processing temperature and device performance. They proposed a solution to this problem by using a-IGZO transparent amorphous oxide semiconducting material as an active channel in transparent thin-film transistors (TTFTs).

Carcia et al. (2005) showed that ZnO thin-film transistors (TFTs) are potentially a higher performance alternative to organic and amorphous-Si TFTs for microelectronics on plastic substrates. They fabricated nanocrystalline ZnO thin-film transistors using low-temperature processing and reported it compatible for flexible electronics on plastic substrates. By controlling the ZnO sputtering, they could engineer the field-effect mobility of ZnO transistors between 2-42 cm²/V.s. They contended that pO₂ controls the oxygen-vacancy content or stoichiometry of ZnO and allows control of transistor field-effect mobility. They showed that properties of nanocrystalline ZnO transistors can be explained using transport models that account for grain-boundary trapping of mobile carriers.

Oh et al. (2010) investigated the visible photon accelerated negative bias instability (NBI) in amorphous In–Ga–Zn–O (a-IGZO) thin film transistor (TFT). They reported the rigid shift in transfer curves with insignificant changes in field-effect mobility and subthreshold swing. It was reported that there is substantial change in capacitance-voltage characteristics caused by created subgap states. They suggested that the nature of the created states is the ionized oxygen vacancy (VO₂⁺) by the combination of visible light and negative bias. Furthermore, the photoexcitation of VO to stable VO₂⁺ yields excess free carriers in conduction band. The increased carrier density enhances the negative shift in turn-on voltage of a-IGZO TFT.

Hosono et al. (2006) have presented a paper on the room temperature fabrication of transparent and flexible thin film transistors on a polyethylene terephthalate (PET) film substrate using an ionic amorphous oxide semiconductor (IAOS) in In₂O₃–ZnO–Ga₂O₃ system. These transistors exhibited a field effect mobility of ~10 cm²/V.s, which were higher by an order of magnitude than those of hydrogenated amorphous Si and pentacene
transistors. Their article described a chemical design concept of IAOS, electron transport properties, and electronic structure. A potential use of IAOS for flexible electronics has been recommended by them.

Chong et al. (2010) reported the time dependence of the threshold voltage ($V_{TH}$) shift in amorphous hafnium-indium-zinc oxide (a-HIZO) thin film transistor under on-current bias temperature stress measured at 60°C. X-ray photoelectron spectroscopy showed the decrease in oxygen vacancies by Hf metal cations in a-HIZO systems after the annealing process. High stability of a-HIZO systems has been observed due to low charge injection from the channel layer. Hf metal cations have been incorporated into the IZO thin films to suppress the oxygen deficiencies and the carrier generation.

Kim et al. (2009) developed amorphous hafnium-indium-zinc oxide (HIZO) thin films as oxide semiconductors and investigated the electrical and physical behavior of the films. The addition of hafnium (Hf) element can suppress growing columnar structure and drastically decrease the carrier concentration and hall mobility in HIZO films. The thin film transistors (TFTs) with an amorphous HIZO active channel exhibited good electrical properties with field effect mobilities of around 10 cm$^2$/V.s, S of 0.23 V/decade, and a high $I_{ON}/I_{OFF}$ ratio of over $10^8$ i.e. adequate enough to drive the next electronic devices.

Jeon et al. (2012) showed that the composition of amorphous oxide semiconductors, which are well known for their optical transparency, can be tailored to enhance their absorption and induce photoconductivity. In principle, amorphous oxide semiconductor based thin film photoconductors could hence be applied as photosensors. They resolved the problem of persistent photoconductivity (PPC) by developing a gated amorphous oxide semiconductor photo thin-film transistor (photo-TFT), that can provide direct control over the position of the fermi level in the active layer. They integrated photo-TFTs in a transparent active-matrix photosensor array to operate at high frame rates and recommended the potential applications in contact free interactive displays.

Orouji et al. (2006) examined leakage current reduction techniques for improving the performance of polycrystalline silicon (poly-Si) thin-film transistors (TFTs) used in
AMLCDs. They presented the idea of making the dominant conduction mechanism in the channel to be controlled by the accumulation charge density modulation by the gate and not by lowering the gate-induced grain barrier. Using two-dimensional and two-carrier device simulation, it was demonstrated that the TG-TFT exhibits significantly diminished pseudosubthreshold conduction leading to several orders of magnitude reduction in the OFF-state leakage current in comparison to conventional poly-Si TFT.

Although information in the literatures on polycrystalline or compound semiconductors and metal oxide are available, the influence of all the material parameter on the TFT characteristics could not be clearly defined. Hence, in an attempt to study the effect of compound semiconductor material of thin film transistor and other possible factors that can have effect on the performance of TFTs, the TCAD (Technology CAD) simulation tool is used in the presented work with an expectation of gaining insight in the physics of the TFTs.