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# Study on Thin-Film Transistor and Circuit Design Using Artificial Intelligence

**Manoharan S.**

Professor, Department of Electrical and Electronics Engineering, JCT College of Engineering and Technology, Coimbatore, India.

**E-mail:** manoish07@gmail.com

## Abstract

This paper reviews the detailed inspection of the current situation of thin-film transistors (TFT) and circuit design using AI, its widespread applications, and the future changes that are about to take place in this field. In liquid crystal display (LCD) systems, thin-film transistors have bridged the gap between the technologies used in this application and have been employed in a wide variety of areas, such as flexible electronics, biological sensing, and integrated IoT platforms. The focus of the paper is on the areas where TFT is heading rather than those it has already traversed. A close look at the sectors reveals that high-resolution displays, where TFT is integrated, result from some vibrant circuits made on flexible substrates, which would not be possible without TFT. Artificial intelligence can be applied to predict and enhance manufacturing efficiency and to estimate costs more accurately. Integrating TFT thin-film transistors with AI integrated circuits in future electronic devices will represent a significant advancement in the field. The AI built-in circuit type augmented by thin-film transistors would unlock visionary progress in entrenched high-tech areas and provide a unique and innovative gateway for businesses and researchers.

**Keywords:** Thin-Film Transistor (TFT), Artificial Intelligence, Liquid Crystal Displays (LCDs), Integrated Circuits (IC's).

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## 1. Introduction

Thin-film transistors, which are primarily used as displays for flat screens and other electronic devices, have also radically improved. The diagonals of the new substrate are already 164 inches. Improvements made in TFTs are not only the result of advancements within the semiconductor layers used and scales of production significant enough to contribute to improvements in manufacturing, but also due to novel enhancements in the devices used for manufacturing. To begin with, the constraints on improvements for these semiconductor layers have been removed. For the last 20 years, liquid crystal displays using TFT technology have been increasingly significant, and this trend is expected to continue. Other applications, however, are becoming more diversified, especially within the sphere of detector types, such as X-ray. In this regard, an area where bioelectronics is applied on a broad scale and is currently active is microelectronics applications like biochemical and chemical sensing, with a focus on organic thin-film transistors (OTFTs) [7]. The next novel biological cell use of TFT arrays is speculated in this paper and aims to utilize them as a substrate for electrical manipulation and possibly sensing. Such applications were neither anticipated nor attempted earlier. With the objective of developing TFTs suitable for biomedical applications, primarily in research related to amyotrophic lateral sclerosis (ALS), experiments were conducted on easily manageable yeast cells. Finally, TFT LCDs will continue to lead all markets in the coming years and will remain a trend. This means that as the technology further enhances its reliability and performance, it will be associated with cost reduction, proliferation, enhancement, and yield increase, following the description of the streamlined gait. TFTs can be made on a variety of substrates. They are foundational to the production of integrated circuits and have versatile applications in flexible electronics. The fact that these devices can accommodate a range of materials and their characteristics makes it likely that we will see a significant emergence of this technology within logic, memory, and sensor technologies in the forthcoming years. Still, challenges related to mechanical robustness within flexible electronics must be overcome by manufacturers. On the new horizon of sensor technologies, innovative examples, such as this one, provide a projection to detect a myriad of properties using carriers and emitted photons.

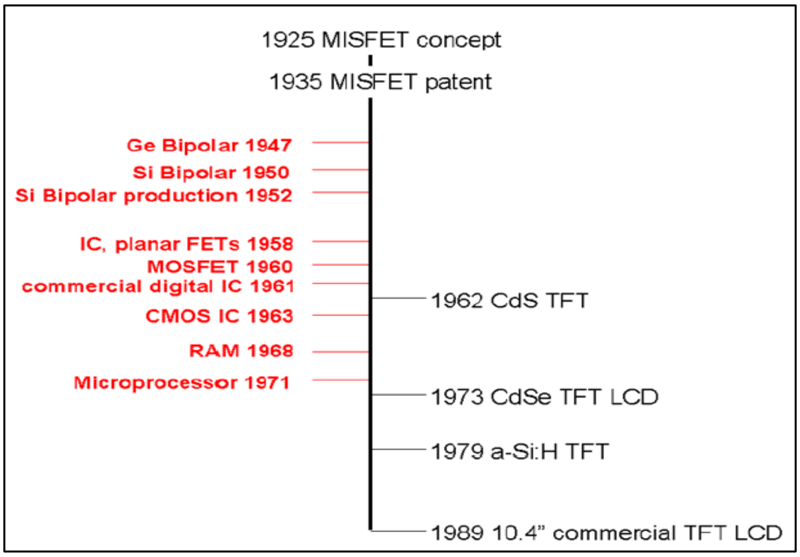

**Figure 1.** History of TFT and IC Development [7]

Figure 1 illustrates the evolution of the last three decades. From the beginning of a-Si TFT research and development projects based on amorphous silicon TFTs, we have advanced to the point where these devices are frequently used and crucial to our daily lives. Additionally, there has been development in the field of displays, which have become an essential component of all modern electronics. The first active-matrix TFTs were designed in the late 1970s and early 1980s after Spear and Le Comber at the University of Dundee reported in the 1970s that hydrogenated amorphous silicon could be doped in a controlled way and used as a semiconductor. The development of interface doping made it easier to activate thin film transistors in activematrix liquid crystal displays, leading to quicker development and production of AMLCDs. Sharp Electronics Corporation initiated these developments by showing a full-color liquid crystal display prototype measuring 3 inches in 1983, as well as a 14-inch TFT liquid crystal display in 1988, which marked a bright future for flat-panel displays as replacements for conventional cathode-ray tube displays. The 1980s focused on technical developments in efficient manufacturing processes, such as the application of etch stopper and channel etch TFT layer structures, in addition to using aluminum gate electrodes that aided in electrical conductivity. The 1980s also saw a paradigm shift towards multi-panel displays and plasma-addressed liquid crystal displays, marking rapid developments in large-screen displays. The 1990s marked a shift towards Low Temperature Polycrystalline Silicon (LTPS) TFTs, permitting greatly improved device performance and pushing their applications well beyond previous expectations. Meanwhile, there was also ongoing research for seamless multi-panel integration as well as improvements in PDP technologies. [6]

However, very few of the initial prototypes were able to proceed to mass production. R&D started concentrating on developing TFTs that were similar to SOI transistors at the start of the twenty-first century. Progress in the growth of long silicon crystals, necessary for high-speed devices, has pushed back those limits via solidification processes of silicon: above all, [1] laser-induced lateral crystal growth. Such demands were met by programs such as ALTEDEC, jointly introduced in 2001 by panel/equipment suppliers and others, which contributed greatly to the development of electrodes, metrology, and R&D for next-generation lithography. Some attemptsendeavored to develop new gate insulator deposition and crystallization processes. The display technology industry also began to turn its attention to next-generation types of devices such as roll-up displays, wearables, and bendable and flexible displays. The rollable organic electroluminescent display on an ultra-thin substrate is such an early example of showing possible applications of flexible displays in the future.

Therefore, since around 2001, collaboration programs such as ALTEDEC have been established by multiple panel and equipment makers and engaged in R&D of next-generation lithography, electrode manufacturing, and metrology technologies for enhancing processes to deposit and crystallize gate insulators. Simultaneously, research was performed by the display industry into new-generation technologies such as wearable, rollable, and flexible displays. A prototype rollable organic EL display that uses thinly rolled substrate materials has demonstrated the inescapable advent of extensive new flexible display technology that will come into regular popular use. However, there has been a major change in the display technologies and consumer electronics industry over the past few years. This is because, by virtue of innovations, the developments in TFT technologies have been accelerated [2]. A major application area where thin-film transistors find use is in the domain of "large area electronic systems" such as "display sensors." However, the LTPS technology complicates and increases the costs of laser crystallization and doping steps, and it is hard to obtain uniform electrical properties for wide areas. This is why, in recent years, system-on-panel (SOP) thin-film transistors using amorphous oxide semiconductors have become increasingly popular. Thin-film AOS TFTs can achieve equivalent mobility to that of n-type a-Si thin-film TFTs and have a similar subthreshold slope and off-current to that of n-type, but are a relatively lower-cost solutionfor large area manufacturing [3].

Through automation, artificial intelligence (AI) has become one of the most effective enabling technologies that are multiplying. Technological advancements in human–machine interfaces over the last decade have made possible the advent of highly autonomous systems, including the manufacturing equipment found in precision engineering, automotive electronics, television systems, and vehicle speed-control circuits. These systems play a key role in daily automation while greatly improving performance and efficiency. The growing availability of consumer data and rising computing power are increasing the usage of AI-powered solutions.

Modern AI-based techniques have revolutionized various industries such as electronics, medical instruments, wireless communication systems, and aerospace technology. Advanced automatic control systems, for example, in Boeing's aerospace industry, are being rapidly incorporated to meet high performance, adaptability, and market demand. The electronics industry is facing similar trends, with companies adopting AI tools to enhance design efficiency and the competitiveness of their products. AI-based software tools are arguably the most influential application of artificial intelligence among industrial applications [4].

AI has also brought hardware technologies and their applications closer to each other, especially in digital and analog IC design. Modern AI-enabled design tools are able to quickly adapt when a circuit-level change is made, offering efficient optimization under constrained resources and improved performance. Nevertheless, challenges exist regarding the accuracy of circuit modeling, threshold evaluation, and design standards. In this regard, a literature review on the role of AI in circuit design and optimization has taken place recently, wherein intelligent modules decompose intricate design problems into well-defined and easy-to-manage steps. Through the use of AI technologies, software applications allow algorithms to imitate some aspects of human reasoning. The software is capable of processing structured, semi-structured, or feature-rich data.

The emergence of 5G communication networks, artificial intelligence, wearable technology, and other related technologies has ushered in the intelligent era of the Internet of Things (IoT). Connected intelligent systems often include information display as one of their key functions. Over the years, flexible display technology has progressed continuously to overcome many of its limitations and has established itself as a new mainstay technology in the display space. Research by universities and companies has continuously created products like foldable phones, curved smartwatches, VR and AR gaming devices, and flexible displays, which have a lot of potential to be used in these products.

The key to smart display technology's advancement is flexible TFT backplane technology, which reduces power consumption while enhancing resolution, frame rates, and overall user experience. Low-temperature polysilicon TFTs (LTPS-TFTs) are potentially better adapted than conventional amorphous silicon TFT (a-Si TFT) backplanes for high-speed and high-resolution displays due to their much higher carrier mobility (>50 $cm^2/V \cdot s$). Additionally, with excellent thermal conductivity and performance stability, LTPS technology is widely used in flexible AMOLED displays for mobile products.

In terms of large-area and low-cost manufacturing, they offer benefits that cannot be obtained with conventional LCD technology. Devices based on amorphous oxide semiconductors (AOS) TFTs can be manufactured at a significantly low temperature (below 350 degrees Celsius) and exhibit moderate carrier mobility, high uniformity, and excellent optical transmittance. Due to these traits, AOS TFTs are ideal for large-area, flexible, and transparent displays. Additionally, scaled oxide semiconductor TFTs have very low off-state currents (less than $10^{-18}$ A/μm) and minimal short-channel effect sensitivity. The device advantages have been substantiated with OLED display prototypes featuring more than 5000 pixels per inch (ppi), suited for VR applications [8].

Apple Inc. has proposed embedded backplane technology based on low-temperature polysilicon and oxide (LTPO) TFTs to meet the growing power consumption that changes depending on the display content. The LTPO TFT technology combines the features of LTPS and AOS. AMOLED displays benefit from LTPO because this technology supports ultra-low 1 Hz refresh rates and multi-frame-rate operation to provide effective power management. The LTPO technology allows several p-type LTPS TFTs and n-type AOS TFTs to be on one substrate. It supports a complementary circuit structure that enhances efficiency, flexibility, and power performance. As a result, next-generation displays will be able to benefit from improved reliability, reduced power consumption, and enhanced design flexibility.

The performance and reliability of flexible TFTs are still quite far behind those fabricated on glass substrates, despite recent advancements. Flexible thin-film transistor (TFT) backplanes, which are manufactured on polymer substrates ranging from polyethylene terephthalate (PET) to polyimide (PI), are likely to receive mechanical and thermal stress. Flexible LTPS TFTs can be unstable due to defects at the grain boundaries and trapping states in the channel. In the same way, the current-driving capacity and photo-induced instability of

AOS TFTs, such as a-IGZO, are also insufficient. Process complexity and material compatibility issues are also encountered by LTPO TFTs.

Tremendous research has been conducted on carbon nanotubes and several two-dimensional semiconductor materials for the application and development of flexible TFTs because of these issues. While these materials are considered to have high mobility, large-scale preparation, uniformity, and cost issues remain. Further studies are needed in process integration and multifunctional system implementation, as well as material development. Recent demonstrations of integrated circuits on flexible substrates for TFT microprocessors, neuromorphic sensing systems, RFID tags, and the like show an expanding application spread and thrust potential for flexible TFT technologies.

This review addresses challenges and solutions related to TFT technologies and circuit design using AI, with special emphasis on process integration, functional optimization, and the development of intelligent TFT-based systems.

## 2. Literature Review

Compact models act as a vital link between how devices are manufactured and how they are designed at the circuit level through the quantitative modeling of transistors for use in simulation. In the case of thin-film transistors (TFT), compact modeling predicts accurately and, at the same time, uses very little computation. This review describes the concepts, development trends, and applications of the TFT compact models related to various active semiconductor materials affecting charge transport properties.

We present an overview of the different TFT compact modeling approaches, focusing on surface-potential-based models for their superior physical accuracy and robustness across operating regimes. The benefits and drawbacks of charge-based and potential-based models are assessed. The paper discusses the novel modeling of organic and IGZO TFTs, which have been developed and parameter-extracted recently using frictional models. Even though work has been done on the new generation of TFT compact models, there is still room for improvement. New models can be mathematically robust, valid in all operating regions, support all simulation modes, and be easy to parameterize.

To fulfill the requirements imposed by the continuously increasing circuit complexity and miniaturization drive for future devices, compact models should incorporate non-ideal effects (contact resistance, gate tunneling, interface states, short-channel scaling effects, and high-frequency operation). To enhance the reliability and performance of TFT circuits under advanced operating conditions, it is important to address these factors [10].

## 2.1 Evolution and Applications of TFT Technology

Analysis by Yue Kuo et al. [7] presents a background analysis of TFT technology, which also includes tracing the history of TFT technology from its inception to possible future directions. This innovation in amorphous silicon TFT technology triggered a revolution in the large-area display industry, resulting in substantial market growth, although the performance potential of the original liquid crystal display technology was very low. Advances in subsequent technologies related to TFT, such as metal oxides, organics, and poly-Si, opened the door to functionalities beyond those of a pixel driver.

Increased substrate size, as well as the ability to produce in high quantities due to equipment advancements, can be identified as some of the important technological advancements. Despite these improvements, challenges still exist, such as material and reliability concerns for flexible and scaled-up electronics. Scalable substrates, sensing in the field of medicine, and multifunctional electronic platforms are expected to be future R&D trends.

Further details regarding the development of TFT technology and its growing role in bioscience and sensing applications can be found in an important review published in the Japanese Journal of Applied Physics (2016) [6].TFT arrays are increasingly being used in physical sensors such as pressure and infrared detectors, chemical and biochemical sensors, and X-ray detectors.Recently, TFTs have been employed as electrical platforms in in vitro bioscience experiments for viability analysis, impedance spectroscopy, dielectrophoretic manipulation, and cell monitoring.These advancements demonstrate how TFT arrays are practical bioelectronic instruments due to their transparency, scalability, and compatibility with dense microelectrode integration.

## 2.2 Emerging AI-Integrated and Neuromorphic TFT Devices

Current research has also investigated new thin-film transistor designs with integrated memory and computing capabilities for artificial intelligence (AI) hardware. One such study aimed at developing a thin-film AI transistor that utilizes skyrmions, or topologically protected magnetic entities, as information bits [11]. This technology integrates double memory cells and logic operations such as NOR and NAND gates based on skyrmion movement through nanowires detected through magnetic tunnel junctions.

The stability of the micromagnetic system to the controlled current densities and boundary conditions, which relied on the Magnus forces and boundary repulsion, was further demonstrated by simulations using the OOMMF software. The potential of skyrmion-based technology to create the next AI hardware platform-which would combine memory and computation at the nanoscale-is further highlighted by this study.

## 2.3 TFT Technology for Large-Area, Flexible, and IoT Electronics

The technology provided by thin-film processing, in relation to the low-cost and flexible process over a large area, has proven to be immensely helpful in the field of present-day electronics. In the TFT process, the semiconductor layer consists of IGZO, a-Si, p-Si, and organic electronics on top of an insulation layer made of glass and polymers. In the formation of the structure of the TFT device, the electrodes-gate, drain, and source-are provided.

Hence, the role of compact modeling in the circuit simulation tool becomes significant, as it enables the rapid computation of circuit performance without relying on intricate physical models. Charge-Based Models and Surface Potential-Based Models are the two general variants. In the first model, there is greater physical understanding within the context of silicon TFTs. Every material has its unique process in terms of the transport of charges. This takes place through hopping in the amorphous/organic TFTs. In poly-Si TFTs, it occurs through grain boundary trapping. In IGZO TFTs, Multiple Trapping & Release Models are ideally applied.

The increasing need for scalability, power efficiency, and adaptability in electronic products and applications can now be adequately addressed and satisfied by the potential benefits and applications presented by TFT technology, which targets the accomplishment of the concepts and realities of the Internet of Things. In fact, the feasibility study for the use of flexible material substrates for RFID, microprocessor development, TFT integrated circuits, and neuromorphic sensors has already been validated in several research studies.

## 2.4 AI-Enhanced TFT Design, Manufacturing, and Reliability

The development of physics models for TFT modeling has advanced significantly, but the integration of AI is still somewhat disjointed. A lack of standard dataset development, a restricted integration of physics-informed AI models, and a lack of end-to-end AI tools for fabrication to system design are some of the problems with current AI technology.

Artificial neural networks, support vector regression (SVR), deep learning (DL), reinforcement learning (RL), and physics-informed neural networks (PINNs) are just a few of the machine learning techniques that have demonstrated significant promise in addressing these research gaps. AI tools can effectively simulate the nonlinear behavior of TFTs in operating conditions that are challenging for conventional compact models when trained with I-V data from experiments. SVR models have outperformed other methods in noisy environments with limited data availability.

PINNs combine traditional governing equations, such as the drift diffusion equation or Poisson's equation, to improve interpretability and reduce the amount of data needed for model development. Changing the TFT procedure to increase the designs' efficiency is a real-world application of reinforcement learning.

Additionally, AI-driven methods have been used to predict aging and bias-stress degradation, reduce spatial non-uniformity in large-area TFT circuits, and improve long-term reliability through adaptive bias control. All of these approaches demonstrate how AI can revolutionize TFT design-for-manufacturing (DfM), performance optimization, and lifecycle management.

## 2.5 Research Gaps

Although the application of AI support functionality within the modeling and optimization process of TFT circuits appears to have promising outcomes, most current attempts remain within the realm of simulation and laboratory implementation. The effective inclusion of AI support functionality within the realm of TFT technologies is contingent upon addressing certain questions, namely manufacturing capability and impact, verification, and integration within the EDA process.

To address fabrication, device simulation, circuit simulation, and system-level optimization concurrently, this work anticipates the need for well-defined data sets, physics-informed AI models, and paradigmatic designs. To improve Internet of Things technology, next-generation displays, and hardware platforms, high-performance and reliable TFT electronics will be developed within this important field.

**Table 1.** Comparasion of TFT Technology

| Ref | Core Objective | TFT Material / Technology | Methodology | Target Application | Limitations / Gaps |
|---|---|---|---|---|---|
| [1] | Develop a complete digital ASIC design flow for TFT-based circuits | Metal-oxide TFTs (n-type) | Standard-cell library design, circuit simulations, synthesis, P&R | Flexible electronics, IoT ICs | Limited to simulation-scale ICs; no fabrication validation |
| [2] | Enable precise droplet control with sensing in AM-EWOD systems | a-Si:H TFTs | Circuit design + simulation + stability analysis | Digital microfluidics, lab-on-chip | High-voltage operation; fabrication complexity |
| [3] | Improve bias-stress stability of TFTs | a-IGZO TFTs with $SiO_2$ / $Al_2O_3$ passivation | Experimental fabrication and stress testing | Display backplanes, reliable TFTs | Focused on device physics, not circuits |
| [4] | Explore early TFT circuit feasibility | CdSe TFTs | Analytical modeling and experiments | Early displays, macro electronics | Outdated materials and low integration density |
| [5] | Integrate storage and computing in TFT-like devices | Skyrmion-based thin-film devices | Device modeling and simulations | AI hardware, neuromorphic systems | Conceptual/simulation-only; non-CMOS compatible |
| [6] | Review TFT evolution and emerging applications | a-Si, IGZO, OTFTs | Comprehensive literature review | Bioelectronics, sensors | No new experimental results |
| [7] | Analyze TFT development trends | a-Si:H, oxide TFTs | Historical and industrial review | Displays, flexible electronics. | Lacks deep circuit-level analysis |

| | | | | | |
|---|---|---|---|---|---|
| [8] | AI-driven design automation | ML classifiers, FPGA, ASIC | End-to-end framework converting datasets into Verilog-based ML classifier ICs | Automated IC design, ML hardware | Moderate accuracy (~80%); limited scalability and generalization |
| [9] | Failure analysis using AI | CMOS, FinFET, GAAFET, TCAD + ML | Transfer-learning-based defect localization with >99% accuracy. | Semiconductor manufacturing, FA | Strong dependence on calibrated TCAD models; high complexity |
| [10] | Circuit-level TFT development | CNT, OECT, organic, oxide, 2D materials | Comprehensive review of digital & analog thin-film circuits | Flexible & large-area electronics | Mostly experimental-scale; limited system integration |

## 3. Discussion

Hence, from the present collection of papers, it is clear that a wide range of views has been offered regarding the development of thin film transistor technology and the incorporation of artificial intelligence in advanced electronics. Viewing it from a larger body of work, it is safe to assume that the adoption of TFT technology is not merely confined to displays but extends to more intelligent electronics. Existing studies on TFT technology at a very early stage focus on the merits of TFT for large-area electronic applications, including flat-panel displays. Additionally, TFT technology is intrinsically inferior in mobility, stability, and scalability to established silicon CMOS technology. The development of TFT materials has attained maturity. Thus far, there have been reported developments in materials such as amorphous silicon, metal oxides, organic semiconductors, carbon nanotubes, and two-dimensional materials that enable low-temperature and flexible processing at low cost. Owing to the properties of TFTs, they are suitable for use in applications beyond the display industry, particularly in sensor applications, such as biomedical sensor interfacing and electronics on plastic substrates or flexible plastics. With the emphasis on display applications for presentations, security has become an important issue in the variations of publications.

The increased TFT reliability through material and process optimization will garner the most attention in experimental TFT research. For example, researchers in the field of passivation for amorphous InGaZnO TFTs have recently demonstrated that the threshold voltage instability is dominated by environmental effects rather than merely charge trapping. Establishing characteristic passivation thicknesses serves as useful guidelines to enhance long-term device stability for practical applications. These supplement the more general reviews that stress the significance of encapsulation and process stability when TFTs are used in non-display applications such as bioelectronics and sensing.

According to the extensive literature, the most significant changes have occurred when AI and machine learning concepts are transparently incorporated into system workflows and device designs. By directly building a Verilog code engine that functions as the classifier circuit in terms of the datasets, one stream of work suggests automation tools to create a close corroboration between the machine learning model optimization and the hardware realization. This method shows new approaches for AI applications in application-specific integrated circuits (ASICs) and FPGA flows, bridging a large gap between algorithm development and hardware implementation, from industrial applications to those in the laboratory. Therefore, in order to fully realize the intelligence of TFT-based systems, it is necessary to take advantage of research opportunities that enhance large-area uniformity, define standards to evaluate artificial intelligence-enabled devices, and capitalize on opportunities for energy efficiency and scale fabrication.

This transistor technology for artificial intelligence represents a significant departure from earlier designs. The development of single-component thin-film AI transistors with logic and memory capabilities is one of the main areas of focus. This includes neuromorphic thin-film transistors, which combine logic and memory, and skyrmion AI devices. Even though the simulation and prototype systems can demonstrate logical operation, synapse behavior, and high identification accuracy, most of these processes are still early-stage prototypes with little practical realization. Unanswered questions remain regarding cost, energy consumption, and large-area integration. Another way to expand applications for TFT technology is through new demonstrations. Present reviews and trials demonstrate that TFT arrays can meet application needs and possess the capability of operating independently of one another, being optically transparent and easily addressable.

This combination of features makes them useful sensing electrodes for chemical, biological, and biomedical applications. This device has capabilities in impedance measurements, dielectrophoresis, and cell monitoring, making it suitable for lab-on-chip and medical applications. TFTs could possibly enable other systems for which CMOS is not viable due to cost, rigidity, lack of process options, etc.

The review papers studied depict the different research of TFT-technology over the years. They have transformed from a display-oriented technology into a flexible platform-a platform from which intelligent, adaptive, and application-specific electronics can be developed. The four basic elements of attaining various levels of computation include investments in materials, control processes for passivation, reliability enhancement advanced technology services, and AI integration at system and hardware levels. A significant gap exists between these laboratory innovations and their real-world commercial applications. As a result, new energy-efficient techniques and better fabrication procedures and device designs from TFTs will allow us to realize the intelligence of these systems. Furthermore, it is necessary to examine research directions toward large-area uniformity and standardization of evaluation of AI-enabled devices.

The most appropriate way to describe TFT devices is by employing artificial neuronal networks and supporting vector regression technology. These are widely accepted techniques in supervised learning algorithms and can even account for non-linear relations between process parameters and electrical properties, which may even comprise the basic physics. The most vital area where ML has made enormous progress because of its defining characteristic application aspect is the application of physics-inspired ML with a high level of generalization within the constraints of real-world TFTs. The following aspects remain yet to be explored under TFT-AI: empirical scale assessment, standardized benchmark datasets, physics-inspired learning paradigms, closed-loop interface between fabrication process data and models, and circuit optimizations with AI.

### 3.1 Research Gaps in TFT-AI Studies and Conceptual Solutions

Although the need for the use of Artificial Intelligence (AI) in the production of thin-film transistors (TFTs) and the circuitry involved has become lively, the research gaps are very deep, thereby hindering the smooth flow of research and its applications, as well as making the lecturers and the researchers restless in their quest to resolve the contradictions in this science.

### 3.1.1 Gap within The Data-Driven AI Models and TFT Device Physics

Above all, most previous work on TFTs and AI is conducted using purely machine learning approaches. These approaches, inspired by data collection, view the device as a black box good at reporting minimal training error and accurately comparing predictions, even in the form of classification via stochastic gradient descent. This corresponds to ignoring transport by traps, bias-stress instability, and process variation. These machine learning approaches lack extrapolation ability within their learning field and render AI forecasts unreliable and untrustworthy. Future research should move forward with physics-informed AI models or hybrid AI models incorporating TFT physics constraints within the learning architecture.

### 3.1.2 The Lack of Integrating AI Applications Across the whole Lifecycle of TFT

AI generally does not work with TFTs down to the process of device modeling, parameter extraction, or even circuit optimization; it still fails because it wasn't originally constructed with the same structure by relating data fabrications of any nQ, TFT behavior, and circuit performance. Meaning, AI can never be fully utilized. Beyond this, current research is working towards an AI framework that encompasses fabrication parameters, which will include device modeling, circuit simulation, and, lastly, system-level optimization. There is now a lot of expectation surrounding Continuous Mock-up, as the live experiment updates the model into a finer tune with real-time, in-field variables in the operation of a closed-loop learning system.

### 3.1.3 Insufficient Experimental Validation and Real-World Datasets

The concept is straightforward: it is generally believed that many published studies on TFT-AI have not been independently verified through real-world experiments. As a result, they rely solely on simulated or limited experimental data, leading them to mistakenly believe that the model is inherently robust and valid for typical industrial use. There is little comparison between studies, not only due to a lack of existent, varied data of a similar scale, but also in the results of the study using the data. As AI models are establishing themselves, these circumstances of demanding ever-increasing amounts of data by rote, symmetrical benchmarks must disappear from communities. To move forward, the same rigorous end-demand would have to become established and accepted within the community. Industry-academic cooperation has always meant large data contributions to include a broad range of things that might become issues concerning process variability while an experiment ages, environmental factors, and a platform to share percentages of that data.

### 3.2 Limited Focus on Reliability, Variability, and Long-Term Behavior

Until now, AI models developed for TFT have mostly focused on determining static electrical attributes. As a consequence, accurate determination of long-term reliability issues, such as bias-temperature stress, hysteresis, and aging, has become obsolete. This, in essence, denies AI for practical applications. Future research should look at time-dependent and uncertainty-aware AI models like probabilistic learning and Gaussian processes in predicting degradation mechanism and variability across a large area of TFT arrays.

### 3.3 Top Three Barriers to Industrial Adoption of AI-Driven TFT Systems

The very first and one of the most significant challenges is a lack of data and its variability. That is because industrial thin film transistor (TFT) processes typically display non-uniformity, dispersion of materials, and data holdings which cannot be accessed externally, respectively, leading to a very limited efficacy of the AI model training.

The next obstacle would be the lack of trust and interpretability, as black-box AI models are quite challenging to validate for reliability-critical operations such as displays, sensors, and biomedical systems. The industry is more inclined to physics-consistent and explainable models that are in agreement with the already existing design rules.

The third main issue is the complexity caused by the lack of integration, as the AI tools at the moment do not intrinsically support the TFT fabrication, TCAD, and EDA workflows. The unavailability of standardized design procedures, verification methods, and qualification frameworks of the AI significantly deter the industry from accepting it at high speed.

## 4. Conclusion

With the integration of AI, a new trend for the future is being developed through thin film transistor and circuit technology. Even though the potential for improvement through the development of the TFT from low temperature polysilicon enhancement of Amorphous Silicon to a-Si:H is quite promising, Amorphous Oxide Semiconductors have easily matured to almost an LTPS backplane technology, which has matured to the most widely used form, now considered the promising technology for ultra-large screen area flexible and consumer electronics with lower costs compared to Silicon technology. Most authors believe that TFT technology has potential use within the context of sensors, bioelectronic modules, microfluidic biosensors, and the IC platform for the Internet of Things. Nevertheless, the major task rests within the low mobility of this particular technology, the uniformity of the large area substrates, and the reduced power consumption for specific applications to the particular circuits of high integration. Otherwise, complementary TFT technologies of ultra-low power standard cell libraries at the circuit level should be significant in facilitating very dense integration. At the same time, new concepts like neuromorphic computing and memory will have to provide first experimental verification for judgment on their energetically efficient manufacturability.

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