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Flexible Amplifiers in a-IGZO TFT Technology

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Technische Universität Dresden

Flexible Amplifiers in a-IGZO TFT Technology

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der Fakultät Elektrotechnik und Informationstechnikder Technischen Universität Dresden

zur Erlangung des akademischen Grades

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KURZFASSUNG

Das Gebiet der biegsamen Elektronik erfährt sowohl von der Wissenschaft als auch von der Industrie beträchtliche Aufmerksamkeit, weil es das Potenzial hat eine Vielzahl von Anwendungen nachhaltig zu beeinflussen. Zu diesen Anwendungen gehören tragbare Audiosysteme, biegsame Photovoltaik, biegsame RFID tags, biegsame biomedizinische Sensoren, biegsame Displays und biegsame Lautsprecher, denn solche Anwendungen können nicht mit herkömmlicher waferbasierter Elektronik angegangen werden. Eine der vielversprechendsten Transistortechnologien für biegsame Elektronik ist die der amorphen Indium-Gallium-Zink-Oxid Dünnschichttransistoren (a-IGZO TFT). Diese Transistoren zeigen interessante elektrische Eigenschaften und können bei niedrigen Temperaturen hergestellt werden. Das ermöglicht es a-IGZO TFTs kostengünstig und auf biegsamen Substraten wie Plastefolie und Papier herzustellen. Die Entwicklung von System-on-Chip (SoC), System-in-Package (SiP), organischer und großflächiger Elektronik (OLAE) sowie Elektronik auf unkonventionellen Trägern hat heute sich zu einem interessanten Forschungsgebiet entwickelt. Hauptgrund dafür ist die feste physikalische Grenze für die weitere Strukturverkleinerung der siliziumbasierten integrierten Schaltkreise, was zum Übergang von der Ära des Mooreschen Gesetzes zur Ära Beyond-Moore geführt hat.

Die beiden Hauptbeiträge dieser Arbeit sind: Die Entwicklung eines SPICE-Modells für a-IGZO TFTs und die Entwicklung von Verstärkerschaltungen in a-IGZO TFT-Technologie für biegsame Anwendungen mithilfe dieses SPICE-Modells. Um diese Anwendungen mit a-IGZO TFTs zu ermöglichen, ist die Entwicklung von Schaltungen zur analogen Signalverarbeitung wie Verstärkern, Oszillatoren und Datenkonvertern notwendig.

Als erster Schritt in Richtung biegsamer Elektronikanwendungen werden Subsysteme wie Bewegungs- und Temperatursensoren sowie Analog- und Hochfrequenz-schaltkreise entworfen. Vor der Fertigung dieser Schaltkreise wurde ein Satz von Design Rule Checks (DRCs) durchgeführt, um eine problemlose Fertigung zu garantieren. Diese DRCs garantieren die Funktionalität

der Schaltkreise selbst wenn sie bis zu einem Radius von nur 5 mm gebogen werden. Mehrere Verstärkerschaltungen verschiedener Topologie wurden mit diesem Prozess hergestellt. Einige der Topologien, wie der Cherry-Hooper-Verstärker und die Verstärker mit induktiver Überhöhung, wurden das erste Mal in einer TFT-Technologie entwickelt. Insbesondere der Cherry-Hooper-Verstärker erreichte eine 3-dB-Bandbreite von 3.5 MHz, so dass ein Betrieb im MHz-Bereich demonstriert werden konnte.

Abstract

The field of flexible electronics is receiving considerable attention from scientific and industrial communities because of its potential impact on a wide variety of applications including wearable audio systems, flexible photovoltaics, flexible RFID tags, flexible biomedical sensors, flexible displays, and flexible loudspeakers, which cannot be addressed by conventional wafer-based electronics. One of the most promising device developed for the flexible electronics technology are the amorphous Indium-Gallium-Zink-Oxide thin-film transistors (a-IGZO TFT). These devices show interesting electrical characteristics and can be fabricated at low temperatures. These features allow the implementation of a-IGZO TFTs on flexible substrates such as plastic foil or paper, and also enables cost effective manufacturing. The development of systems on a chip (SOC), system in a package (SIP), organic and large-area electronics (OLAE), and electronics on unconventional substrates has become an interesting research area nowadays, mainly due to the inevitable down-scaling limit on silicon-based electronic devices which has led to the transition from the era of Moore's law to the beyond Moore era.

This thesis presents two major ideas: First, a development of a SPICE model for a-IGZO TFTs, and second being design of TFT amplifier circuits targeting flexible electronics applications, using the developed model. To enable such applications with a-IGZO TFTs, the development of analog processing circuits, such as amplifiers, oscillators, and data converters, are needed.

As the first step toward the development of flexible electronics applications, subsystems like motion and temperature sensors, analog and radio frequency (RF) circuits are designed. Prior to the fabrication of these circuits, a set of design rule checks (DRCs) were performed for manufacturability. These DRCs guarantee the functionality of the circuits even when the flexible substrates are bent to a radius of 5 mm. Several amplifiers with different topologies were fabricated using this process. Some topologies like Cherry-Hooper amplifier and amplifier using inductive peaking technique are developed for the first time in TFT

technology. The Cherry-Hooper amplifier in particular exhibited a 3 dB bandwidth of 3.5 MHz, thereby demonstrating operation in the megahertz regime.

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LIST OF ABBREVIATIONS AND ACRONYMS

Symbol	Description
AF	Audio frequency
AM	Amplitude modulation
Au	Gold
Al_2O_3	Aluminum-oxide
ALD	Atomic layer deposition
a-IGZO	Amorphous Indium-Gallium-Zink-Oxide
a-Si:H TFT	Hydrogenated amorphous silicon thin-film transistor
ADS	Advanced designed system
A_F	Feedback voltage gain
a	Voltage gain
BW	Bandwidth
CS	Common-source
CG	Common-gate
Cr	Chromium
C_g	Gate capacitance
C_{ch}	Channel capacitance
C_{ov}	Overlap capacitance
CAD	Computer aided design
C_{ox}	Oxide capacitance (transistor)
CMOS	Complementary metal-oxide semiconductor
dBV	dB referenced to 1 V (rms)

DRC	Design rule check
Def0	Dark fermi level
E_{str}	Gate bias stress field
f_t	Transit frequency
g_m	Transistor transconductance
g_{ds}	Transistor drain to source transconductance
GBWP	Gain-bandwidth-product
GDS	Graphic data system file
HF	High frequency
HP	High power
Iol	Zero-bias leakage current
I_D	Drain current
IC	Integrated circuit
IPCB	Inject printed circuit board
k	Boltzmann's constant
L_{ov}	Transistor gate to source / drain overlap length
LVS	Layout-vs-schematic
L	Transistor channel length

MOSFET	Metal-oxide-semiconductor field-effect transistor
NMOS	n-channel MOSFET
N_a	Channel doping
n_i	Intrinsic carrier concentration
OLED	Printed organic LED
OSMD	Oppositely-stacked MOS diode
OOK	On-off keying
OFET	Organic field-effect transistor
PM	Phase margin
PECVD	Plasma-enhanced chemical vapor deposition
PCB	Printed circuit board
q	Unit charge
RPI-aTFT	Rensselaer polytechnic institute-amorphous TFT
R2R	Roll to roll
r_o	Intrinsic output resistance of a transistor
RF	Radio frequency
RFID	Radio-frequency identification
SiNx	Silicon nitride
Sigma0	Minimum leakage current
SIP	System in a package

SOC	System on chip
T	Absolute temperature
Ti	Titanium
TOLAE	Thin-film and organic large area electronic system
TFT	Thin-film transistors
T_{ox}	Oxide thickness
UV	Ultraviolet
V_{DS}	Drain-source voltage
V_{th}	Threshold voltage
V_{GS}	Gate-source voltage
VGA	Variable gain amplifier
V_{DD}	DC supply voltage
V_A	Early voltage
V_s	Band bending
W	Transistor channel width
W/L	Width over length ratio (transistor)
ω	arbitrary angular frequency
ω_0	angular chirp starting frequency
ZnO	Zink-Oxide
μ_n	Mobility of charge carriers in the channel of an n-type transistor

$\mu_{FET,lin}$	Effective field-effect mobility in the linear regime
$\mu_{FET,sat}$	Effective field-effect mobility in the saturation regime
ε_0	Vacuum permittivity
ε_r	Relative permittivity
ΔL	Channel length variation
ΔV_{th}	Threshold voltage shift
λ	Channel length modulation
$\partial/\partial.$	first partial derivative operator

1 INTRODUCTION

1.1 Motivation

Transparent electronics is a rapid growing field that has gained a lot of attention and interest from researchers in academic and industrial areas around the world, especially in the last decade. This motivation was mainly maintained by the first report on thin-film transistors (TFTs) for transparent electronics published in [1]-[3], all of them employed a Zink-Oxide (ZnO) as the channel layer material. One year later, Nomura et al. reported the successful work on the fabrication at room-temperature of transparent TFTs on flexible substrates using an amorphous Indium-Gallium-Zink-Oxide (a-IGZO), as the active layer material [4]. This active layer demonstrates higher carrier mobility in comparison to the other amorphous semiconductors employed in TFTs, namely hydrogenated amorphous silicon thin-film transistor (a-Si:H TFT) which is largely used in solar cells and flat panels. Later, the flexible electronics technology has been improved to a certain level of performance that promises to change the daily life of people all over the world.

Due to these researchers' works, mechanically flexible and therefore bendable devices can be integrated as a bendable electronic system for wearable devices, textiles, or healthcare equipment, and therefore lead to a wider functionality of everyday objects [5],[6]. In addition, quite new flexible applications such as bendable displays, bendable loudspeakers, or smart RFID (radio-frequency identification) tags seem to be possible for realization.

Regardless of the device bendability, flexible electronics introduces two additional benefits in comparison to the standard silicon technology. First, the fabrication process can be proceed in lower temperatures that make possible the use of flexible substrates such as plastic and paper. Therefore size and weight are not comparable with the available single crystalline semiconductor wafers. Second, bendability of the flexible large scale substrates leads roll to roll (R2R) fabrication method. However, it has to be mentioned that the operational stability and operational frequency of TFTs and complexity of TFT circuits cannot compete with circuits in semiconductor wafers. By the way, this technology is still not matured and needs to be improved, and as the moment of writing this thesis, several improvements proposals are being investigated on this subject.

Today, most TFT-based applications are largely limited to digital circuits. However, it is also necessary to consider circuit designs in analog domains to fill the gap between the analog and digital worlds. This can only be achieved with circuits that can handle analog signals with comparable performance and reliability level as those designed and implemented in digital subsystems. Some valuable works have been carried out in recent years concerning mechanical and electrical performance improvement of a-IGZO TFTs, and analog circuit designs [6],[7].

This thesis investigates and describes a collection of amplifier circuit topologies and techniques for its use in analog signal processing with special requirements for targeted applications such as: flexible AM (amplitude modulation) shortwave radio receive, printed loudspeaker driver, On-Off Keying (OOK) receiver, temperature sensor, and motion sensor.

1.2 Scope of Application

This work was partly funded by the European Commission, under project FLEXIBILTY (Flexible Multifunction Bendable Integrated Light-Weight Ultra-Thin Systems) and the German Research Foundation (DFG) within the Organic Path Cluster of Excellence “Center for Advancing Electronics Dresden”. The goal of the FLEXIBILITY project [8],[9] is advancing the competitiveness of Europe in the area of multifunctional, ultra-lightweight, ultra-thin, bendable thin-film and

Table 1-1: Participants and main tasks

TECHNISCHE UNIVERSITÄT DRESDEN	TUD	Coordination, audio amplifier, broadcast and data radios
Enfucell	ENF	Primary batteries
pm TUC	TUC	R2R printing and fabrication, speakers, audio oscillator
SIEMENS	SIE	Sensor systems and packaging
ETH	ETH	IGZO thin film technology and fabrication
EXODUS e.SOLUTIONS	EXO	Wireless streaming platform e.g. for advertisements and web page
DATA CONTROL SYSTEMS	DCS	Sensor platforms e.g. for security and food
Smartex	SMA	Textile integration, wearable audio system, and packaging
VARTA	VAR	Secondary batteries e.g. rechargeable batteries
KONARKA	KON	Solar cells e.g. OPV to battery interface electronics
VTT	VTT	Touch screen and user interfaces
BELECTRIC Belectric OPV GmbH	BEL	Solar cells e.g. OPV to battery interface electronics

organic large area electronic systems (TOLAE). With TOLAE, technology systems can be fabricated on a simple piece of plastic foil or even paper resulting in low fabrication costs per area [9]. Developed TOLAE components consist of disposable and rechargeable batteries, organic solar cells, DC charging electronics, printed piezoelectric loudspeakers, flexible audio amplifiers, analog signal generators, temperature and motion sensors, receiver circuits, and touch screens.

There were several partners from Austria, Finland, Germany, Italy, Greece and Switzerland in FLEXIBILITY involved dealing with the different aspects of the entire approach. Table 1-1 summarizes the participants and their main tasks.

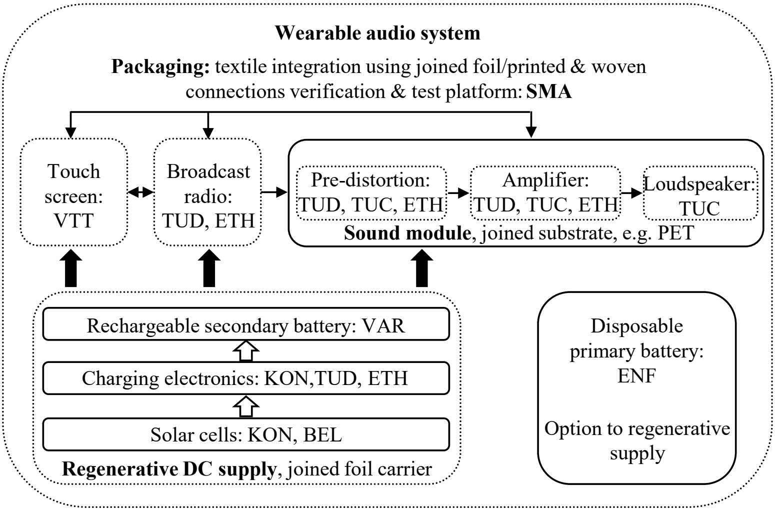

Fig. 1-1: System architecture of the flexible wearable audio system.

The FLEXIBILITY group has access to a large number of flexible technologies suitable to implement a wide range of functional electronic systems for flexible or wearable applications: disposable and rechargeable batteries, organic FET transistors (OFETs), flexible TFTs, flexible temperature and motion sensors, printed organic LEDs (OLEDs) and touch screens, textile and printed antennas, and textile integration technology. The project aimed at designing and implementing mechanically flexible multifunctional systems such as AM shortwave radio receiver for wearable applications or integrating components in packaged flexible systems. The main goal of the FLEXIBILITY is further improvement in developing all the available technologies to facilitate their integration into bendable or flexible wearable systems, making them electrically and functionality adaptable each with all others [9]. In FLEXIBILITY, three of such systems were proposed as a planning phase of the project for showing the potential of the consortium technologies [9],[10]: 1) Textile integrated audio module with integrated AM shortwave radio, and solar supply; 2) wireless streaming of audio data and advertising by active receiver tag; 3) motion or temperature sensor for soft book. Fig. 1-1 represents the architecture of the audio module with broadcast radio receiver which is the most critical application in this project. The system includes various integrated flexible modules, which are a broadcast radio receiver and a sound module with driving electronics.

For the implementation of such mechanically flexible system, the features of various low-cost TOLAE technologies are integrated. Microscale (down to 2 μm), fast (transit frequency > 200 MHz, carrier mobility > 7.5 $cm^2V^{-1}s^{-1}$) a-IGZO TFT [11] technology allows wireless communication systems. The R2R printing method is used for elements requiring large areas such as piezoelectric loud speakers, high-power OFETs, solar cells, and 3-D integration, as well as implementation of heterogeneous devices on one single substrate. Scalable model templates and therefore design-kits in advance design CAD tools are developed for simulating and drawing layout to enable efficient circuit development. Interface and packaging challenges are studied for full system integration on one flexible plastic foil with maximum bending radius of 5 mm.

1.3 Objectives and Structures

This work presents a structured approach for the design of several amplifiers using TFT technology for targeted applications in the project. Key points of investigations are as follows:

- **Thin-film transistors:** The electrical properties of the a-IGZO TFT, the device structure, and its manufacturing process are introduced.
- **Modeling:** AC and DC characteristics of a-IGZO TFTs are performed, and a TFT-based model template is introduced and developed for circuit designs, as well as drawing layouts of the circuits.
- **Design and theory:** Several technologies of amplifiers are introduced in the frame of defined applications in FLEXIBILTY project. Methods for designing of all major blocks for the targeted systems are presented. The limitations of technology which have effects on the circuit performance are introduced. Then, such these topologies are developed in order to be able to reduce these effects such as the effect of threshold voltage shift in a-IGZO TFTs due to constant biasing. Finally, a fully integrated wearable audio system including a complete AM radio receiver

and loudspeaker driver systems, charging electronics, and textile antenna is developed, which combines all analog and digital building blocks.

The focus of this work is on circuit designs. It is not intended to provide a thorough discussion on device fabrication, technology limitations, and device modeling which are reported mostly by previous works [6],[7]. However, it is necessary for verification of the whole system; a TFT model template is developed and applied, but the detailed procedure is described only as much as necessary for general understanding.

1.4 Thesis Outline

This thesis is structured as follows:

- **Chapter 2** provides a theoretical background regarding the subjects of a-IGZO semiconductor operation, transistor basics, and device structure. Moreover, limitations of the a-IGZO technology is introduced.
- **Chapter 3** is devoted to the SPICE model template based on a-IGZO TFT, and implemented in an advanced design simulator written in behavioral language Verilog-A. DC and AC parameters have also been extracted for several single a-IGZO TFTs. The DC RPI-aTFT model has been developed and adapted to the a-IGZO TFTs to take scalability of the device into account. A higher-order AC approximation model is also introduced to improve the simulation of a-IGZO TFT behavior at high frequencies. In addition, layouts of the components which are fabricated based on this technology such as transistors, resistors and capacitors will be introduced. All of these concepts are presented in this chapter in order to familiarize the reader to some of the specific topics that were involved in the work.
- **Chapter 4** provides the methodology behind the design process of the amplifier, circuit classifications, and the measurement setup.
- **Chapter 5** provides the design of integrated circuits, circuit analyses, and their measurement results in detail. Furthermore, the measurement results are compared with the similar published works in TFT technology.

- **Chapter 6** is the final chapter of this work. It presents the conclusions which are achieved from the work, proposals for future improvement of the proposed topologies, and potential applications that can be constituted using the produced amplifiers.

References

[1] S. Masuda, K. Kitamura, Y. Okumura, S. Miyatake, H. Tabata, and T. Kawai, "Transparent thin film transistors using zno as an active channel layer and their electrical properties," *Journal of Applied Physics Letters*, vol. 93, no. 3, pp. 1624–1630, February 2003.

[2] R. L. Hoffman, B. J. Norris, and J. F. Wager, "Zno-based transparent thin-film transistors," *Journal of Applied Physics Letters*, vol. 82, no. 5, pp. 733–735, February 2003.

[3] P. F. Carcia, R. S. McLean, M. H. Reilly, and G. Nunes Jr., "Transparent zno thin-film transistor fabricated by rf magnetron sputtering," *Journal of Applied Physics Letters*, vol. 82, no. 7, pp. 1117–1119, February 2003.

[4] K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano, and H. Hosono, "Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors," *Letters to Nature*, vol. 432, no. 7016, pp. 488–492, October 2004.

[5] A. Nathan, A. Ahnood, Matthew T. Cole, Sungsik Lee, Y. Suzuki, P. Hiralal, F. Bonaccorso, T. Hasan, L. Garcia-Gancedo, A. Dyadyusha, S. Haque, P. Andrew, S. Hofmann, J. Moultrie, Daping Chu, A.J. Flewitt, A.C. Ferrari, M.J. Kelly, J. Robertson, G. Amaratunga, and William I. Milne, "Flexible electronics: The next ubiquitous platform," *Proceedings of the IEEE*, 100(13):1486–1517, May 2012.

[6] N. Münzenrieder, "Flexible oxide semiconductor electronics on plastic," *substrates.url={http://e-collection.library.ethz.ch/view/eth:7908}, PhD thesis ETH Zürich*, October 2013.

[7] B. F. G. de Silva, "Analog Circuit Design with Transparent Electronics," *PhD thesis, Faculty of Engineering*, University of Porto, July 2013.

[8] www.flexibility fp7.eu, "EC Integrating Project Flexible, Organic and Large Area Electronics and Photonics (FLEXIBILITY)," *FP7-ICT-2011.3.6*; Grant Agreement Number: 287568.

[9] C. Carta, K. Ishida, B. Kheradmand-Boroujeni, R. Shabanpour, T. Meister, G. Schmidt, E. Suomalainen, A. Brandlmaier, G. A. Salvatore, N. Munzenrieder, L. Petti, G. Troster, D. Petrantonakis, D. Kozakis, R. Paradiso, M. Krebs, M. Tuomikosko, H. J. Egelhaaf, and F. Ellinger, "Overview of the EC Project FLEXIBILITY: Organic and Thin-Film ICs up to Radio Frequencies for Multifunctional Flexible Systems," *SBMO/IEEE MTT-S International Microwave & Optoelectronics Conference (IMOC)*, pp. 1-2, August 2013.

[10] F. Ellinger, C. Carta, A. Hubler, G. Schmidt, J. Zapf, G. Troster, A. Talo, D. Kozakis, D. Vassiliadis, R. Paradiso, M. Krebs, M. Scharber, and M. Tuomikoski, "Organic and large-area electronic (OLAE) technologies for smart textiles (Chapter 9)," *In Multidisciplinary know-how for smart-textiles developers*, *Woodhead Publishing Series in Textiles*, T. *Kirstein, Ed. Cambridge, UK, Woodhead Publishing Ltd.*, pp. 253 – 284, 2013.

[11] N. Munzenrieder, L. Petti, C. Zysset, G. A. Salvatore, T. Kinkeldei, C. Perumal, C. Carta, F. Ellinger, and G. Troster, "Flexible a-IGZO TFT ¨ amplifier fabricated on a free standing polyimide foil operating at 1.2 MHz

while bent to a radius of 5 mm," *IEEE International in Electron Devices Meeting (IEDM)*, pp. 5.2.1–5.2.4, December 2012.

2 TRANSISTOR BASICS

2.1 Introduction

Thin-film transistors (TFTs) using a-IGZO technology have been fabricated on a free-standing polyimide foil. They are based on bottom-gate structure, which isolates the channel from the substrate. These two structural aspects make TFT device electrical characteristics independent of the substrate bias voltage, which is an advantage compare to metal-oxide-semiconductor field-effect transistor (MOSFET).

The device structure and electrical properties are described in the following sections:

2.2 Device Structure

Fig. 2-1 presents the corresponding cross section of the bottom-gate a-IGZO TFT fabricated on a 50 µm-thick (Kapton E from DuPont) free-standing polyimide foil, which has no electric influence on the device operation. The device is fabricated by standard ultraviolet (UV) lithography. The channel material is not embedded in the substrate, and instead deposited in the semiconductor material on top of the substrate.

In this work three types of a-IGZO TFT are used: High frequency (HF) self-aligned and non-self-aligned a-IGZO TFT, and high power (HP) a-IGZO TFT.

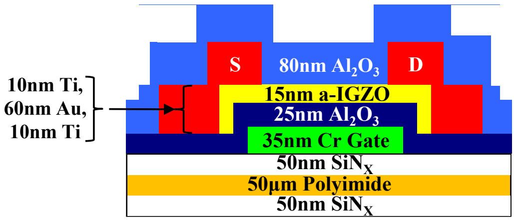

Fig. 2-1: The device cross section of bottom-gate a-IGZO TFT including layer materials and thicknesses.

At the moment, the available oxide semiconductor TFT technology only provides n-type TFTs.

The non-self-aligned a-IGZO device is fabricated using five photography masks (five-layer process). The device is manufactured as follows [12]:

As it was mentioned above, a 50 µm-thick polyimide foil is used as flexible substrate. A 50 nm-thick SiN_x is deposited on both sides of the substrate to increase the adhesion between the substrate and all other material layers by PECVD. A 35 nm-thick Chromium (Cr) is used to fabricate the gate contact in order to provide a better adhesion in comparison to the most other metals. A 25 nm-thick (80 nm for HP a-IGZO TFTs) Al_2O_3 is deposited as a gate insulator, which can provides a high dielectric $\varepsilon_r = 9.5$. The gate insulator is fabricated by ALD with the highest temperature of 150ºC. Then, a 15 nm-thick semiconductor (amorphous IGZO) is sputtered in room temperature. A 10 nm-thick Titanium (Ti) and a 60 nm-thick gold (Au) are used to fabricate the source and drain contacts. Finally, passivation of the device is done by deposition of the additional 25 nm-thick layer of Al_2O_3.

Self-alignment of the source and drain contacts has been used to fabricate shorter channel length devices up to 0.5 µm, and a gate-to-source / drain overlap (L_{ov}) of 1.5 µm [13]. However, L_{ov} in the non-self-aligned technology for HF and HP TFTs are 5 µm and 15 µm, respectively. The fabrication process of self-aligned a-IGZO TFTs are the same as non-self-align devices, however, Ti is used to fabricate the gate contact, and Cr and Au are used to fabricate gate and drain contacts. Comparable to standard silicon technology, self-alignment can be