Design, Automation, and Test for Low-Power and Reliable Flexible Electronics

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Contents

Abstract

Flexible electronics are emerging as an alternative to conventional Si electronics for smart sensors, disposable RFID tags, and solar cells. By utilizing inexpensive manufacturing methods such as ink-jet printing and roll-to-roll imprinting, flexible electronics can be made on low-cost plastic films just like printing newspapers. However, the key elements of flexible electronics, thin-film transistors (TFTs), have slower operating speeds and are less reliable than their Si electronics counterparts. Furthermore, TFTs are usually mono-type – either p- or n-type – devices. Making air-stable complementary TFT circuits is very challenging or sometimes not feasible to most TFT technologies. Existing design methodologies for Si electronics, therefore, cannot be directly applied to flexible electronics. Other factors such as high supply voltage, large process variation, and lack of trustworthy device modeling also make designing larger-scale and robust TFT circuits a significant challenge.

The objective of this article is to provide an in-depth overview of flexible electronics from their applications, manufacturing processes, device characteristics, to circuit and system design solutions. We first introduce the low-cost fabrication methods for flexible electronics, including ink-jet printing, screen printing, and gravure printing. The device characteristics and compact modeling of several major TFT technologies will be illustrated. We will then give an overview of digital and analog circuit design from basic logic gates to a microprocessor, as well as design automation tools and methods, for designing flexible electronics. We also describe a reliability simulation framework that can predict TFT circuits' performance degradation under bias-stress. This framework has been validated using the amorphous-silicon (a-Si) TFT scan driver for TFT-LCD displays. Finally, we will give an overview of flexible thin-film photovoltaics using different materials including amorphous silicon, CdTe, CIGS , and organic solar cells.

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1

Introduction

In 1947, Shockley, Bardeen, and Brattain invented the first transistor at Bell Labs, which opened the era of solid-state electronics. In 1958, Jack Kilby of TI invented the first integrated-circuit (IC) in which he successfully assembled several electronic components to form a miniature circuit. In 1965, Intel co-founder Gordon Moore published a paper in the Electronics magazine which predicted that the number of transistors per IC would double about every two years, later known as the Moore's Law Moore [April 19, 1965]. In 1971, Federico Faggin of Intel successfully demonstrated the world's first microprocessor, Intel 4004, running at a clock rate of 108 KHz with 2,300 transistors in a 10-μm pMOS technology. In the last 40 years, we have witnessed the tremendous impact of the IC technology that has brought to the world since its debut. The abundant computing power that comes from faster and cheaper transistors has made our world today very different from what it was 40 years ago. For the future of the semiconductor industry, the ongoing debate has been centered around questions like: "Is the Moore's law going to continue?" and "Will the rigid and disc-like silicon wafer and the printed circuit-board (PCB) continue to be the dominant ways to make electronics for future applications?"

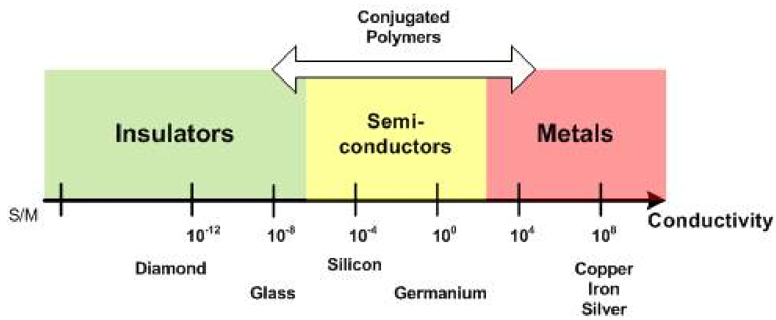

Figure 1.1: Conductivity of conjugated polymers

1.1 Plastic Electronics Revolution

In 1977, 30 years after the first transistor was invented, Heeger, MacDiarmid, and Shirakawa published their discovery of conductive polymer in Shirakawa et al. [1977] and received their Nobel Prize in Chemistry in 2000. Plastic, which is made of polymer, is usually viewed as an insulator and not conductive to electron transportation. In their discovery, however, by proper doping or oxidation, polymers can also be as conductive as metals if the conjugated chains can be properly aligned. The conductivity of polymers is shown in Figure 1.1. This discovery creates alternatives of making electronics, which is not limited to hard and rigid silicon wafers and PCBs. As of today, thousands of semiconducting materials are suitable to make flexible electronics, which brings our imagination of many sci-fi gadgets closer to reality. For example, amorphous-Si, organic and transparent metal-oxide thin-film transistors (TFTs) are considered promising candidates for flexible electronics. We will give an in-depth overview of TFTs in Chapter 3. Although the carrier mobility of organic materials is still significantly slower ($10^{-2} \sim 10^{-3}$X) than that of crystalline and poly-crystalline Si, the steady pace of improvement to their mobility has made organic digital and analog circuits feasible, which can complement to, or may eventually compete with, silicon electronics for certain applications.

1.2 Large-Area Applications

One of the key advantages of flexible electronics is its low manufacturing cost on large-area substrates. Since most organic materials can be converted to a liquid phase, which can be used as functional "inks", manufacturing organic circuits is similar to printing newspapers for which roll-to-roll or ink-jet printing can be used. An overview of the manufacturing methods will be described in Chapter 2. For these low-cost manufacturing methods, several kinds of flexible substrates, such as thin-glass, metal foil, and plastic films, can be used. The manufacturing cost per unit area can be as low as one hundredth of that of silicon electronics. On the other hand, in contrast to silicon electronics that often require sophisticated heterogeneous integration of silicon VLSI chips, discrete passive elements, and ceramic packages on rigid epoxy-resin glass fabric printed circuit boards (PCBs), flexible electronics can be made through homogeneous integration of active printed circuits, encapsulation, and thin-film ($< 100\ \mu$m in thickness) substrates, which can be fabricated with a much simpler process and material treatment. This advantage in integration can significantly reduce manufacturing costs. Furthermore, since semiconductor materials for flexible electronics do not require high process temperature and high vacuum that are indispensable for conventional silicon electronics, the energy consumption and the material cost of fabricating flexible electronics are much lower than those for silicon electronics. Sakurai(2007) shows a comparison of cost per unit area between organic and silicon VLSIs indicating that the manufacturing cost of organic ICs is only one hundredth of silicon VLSIs for a 10cm by 10cm area and it can be even lower for high-volume production.

The low manufacturing cost on large-area flexible substrates enables many applications that are not economically practical or mechanically infeasible with conventional silicon electronics. Figure 1.2 shows several applications of flexible electronics, ranging from low-cost RFID tags, flexible displays, artificial skins for robotics, solar cells, to large-area wireless power-sheets. Instead of using multi-billion-dollar foundries for fabrication, electronics for these applications can be mass-produced

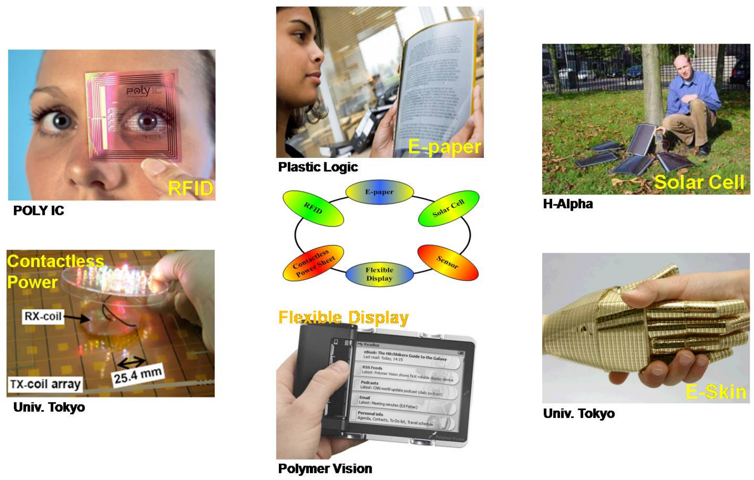

Figure 1.2: Typical applications of flexible electronics

on large-area flexible substrates using simple printing facilities. This is particularly advantageous for those applications that require fast prototyping, demand customization, or have a small volume such as wearable sensors, disposable biochemical testers as well as personalized healthcare devices. With low capital investment and high flexibility in configuring printing facilities, the manufacturers will be able to easily adjust their production lines as simple as changing the printed contents and quickly deliver new electronic products to meet fast-changing tastes of the consumers.

1.3 Differences from Silicon Electronics

Thin-film transistors (TFTs), the key elements of flexible electronics, can be fabricated using simple process steps (usually less than 5 masks) at a low process temperature on inexpensive flexible substrates such as Polyethylene Terephthalate (PET) plastic films, which help lower the manufacturing costs. An overview of TFT technologies will be described in Chapter 3. Compared with MOSFETs, printed TFTs have larger feature sizes ($\sim 10^3$X) due to their low-cost printing processes, which inevitably introduce larger layout-dependent parasitic resistance and

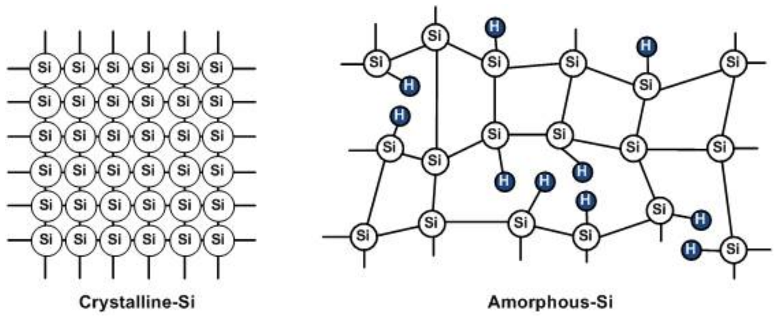

Figure 1.3: Atomic structure of single crystalline-Si and amorphous-Si

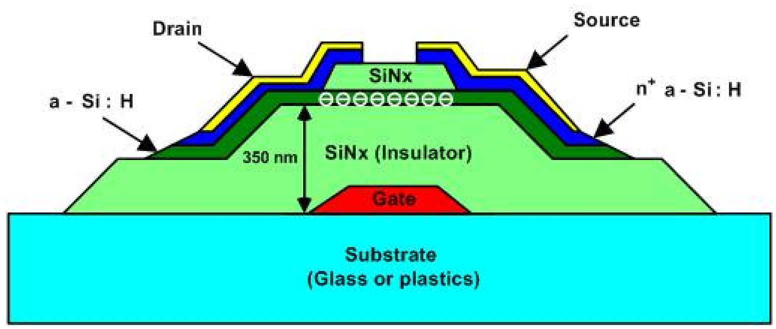

Figure 1.4: Device structure of a hydrogenated amorphous silicon (a-Si:H) TFT. (The white circles show that the high density of defects can trap carriers near the semiconductor and insulator interface).

capacitance and therefore limit their operating speeds. On the other hand, although low process temperature can reduce the manufacturing cost and energy consumption, semiconductor materials made with this low process temperature are usually amorphous and have many dangling bonds as illustrated in Figure 1.3. This amorphous atomic structure limits the carrier mobility and causes reliability concerns during the operation because the carriers could be trapped in the dangling bonds and alter the device properties.

1.4 Challenges for Circuit and System Design

In addition to the reliability concerns, the high supply voltage ($> 20V$) and mono-type device (only either p- or n-type, but not both, is available) also make designing low-power TFT circuits a challenging task. Figure 1.4 shows a typical device structure of a-Si:H TFT, in which the gate insulator material is hundreds-nanometer thick amorphous silicon-nitride (a-SiNx). The a-SiNx material has many advantages in manufacturing such as low process temperature, high uniformity across a large area with plasma-enhanced chemical-vapor-deposition (PECVD), and a relatively high dielectric constant ($\epsilon_r \sim 7$). In order to suppress the gate leakage problem, however, the a-SiNx layer needs to be kept sufficiently thick due to its inferior quality to the thermally-grown SiO_2 gate insulator in Si-MOSFET. As a result, a high supply voltage is required. On the other hand, unlike Si-MOSFET, in which the device-type (p- or n-type) can be determined by doping either p-type (ex. Boron) or n-type (ex. Phosphorus) materials into intrinsic Si, the device-type of TFTs is determined by the majority carrier of the material. For instance, a-Si:H and metal-oxide materials (ex. InGaZnO and ZnO) are n-type, in which the majority carrier is the electron, while most organic materials, including small-molecule and polymer, are p-type and their major carrier is the electron hole. With only mono-type TFTs, the widely-used CMOS design cannot be directly applied to TFT circuit design. This attribute causes many challenges in circuit design for achieving high noise margin and low leakage power which are required for large-scale circuits.

Furthermore, unlike mature single crystalline-Si manufacturing of which the process variation is well-controlled (often less than 5%), process variation of flexible electronics using these low-cost manufacturing methods is very significant. This adds extra challenges for designing flexible circuits and a fabricated circuit could have substantial deviation from its target performance. Other factors such as the process-temperature dependent dimension deformation (ex. shrinking or expanding) of flexible substrates and environmental instability (ex. chemical degradation due to moisture or oxygen contents in the ambient air) also make realizing a robust flexible circuit a very challenging task.

For flexible electronics applications, system-level solutions to build a reliable system based on unreliable devices are equally important to, if not more important than, device- and circuit-level solutions. For example, a system-level solution to electronic textiles (*e*-textiles) was proposed in Park et al. [2002], Marculescu et al. [2003], Stanley-Marbell et al. [2003]. *E*-textiles are computational fabrics that form a large-area, flexible, and conformable information system for both consumer electronics and aerospace/military applications. A *Model of Colloidal Computing* Marculescu and Marculescu [2002] is introduced to provide mechanisms for extracting useful work out of the unreliable elements. Two techniques, *code migration* and *remote execution*, are proposed to provide feasible means of adapting to failures in the presence of redundancy Marculescu et al. [2003], Stanley-Marbell et al. [2003].

1.5 Summary

With rapid advances of flexible semiconducting materials, the performance of TFT circuits has been improving significantly and the concerns of their ambient stability have been alleviated to a great extent in the past few years. After a brief introduction to flexible electronics, this chapter highlights its key difference from silicon electronics, and the challenges and opportunities of circuit design for emerging applications such as wearable electronics, personalized healthcare, and flexible displays. While the main objective of this overview article is on the design, EDA and test issues, we also offer brief technical reviews on TFT technologies, manufacturing methods, and flexible photovoltaics for the purpose of providing a more comprehensive introduction of this emerging field.

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