

Chapter 2

Applications of Large-area Electronics on Foil

Applications addressed by large-area electronics give the motivation to push further the research on large-area TFT manufacturing processes and circuit design. Since the birth of electronics, the main research goals have been miniaturization and increasing computational power. Today's focus is turning back to people, and electronics aims now to pervade everyday life. From this prospective, standard transistor technologies do not provide anymore a solution suitable to all demands. For innovative applications mechanical properties may become more important than performance, or cost must be sometimes evaluated with respect to the area and not to the complexity of the function realized. In this chapter, several applications enabled by large area electronics on foil will be reviewed.

2.1 From Miniaturization to Flexible Substrates

The first integrated circuits date back to the 1950s. Since that moment, the miniaturization of the metal-oxide-semiconductor field effect transistors (MOSFETs) has enabled enough computational power for lots of applications ranging from medicine to gaming, from aviation to video editing, from automotive to telecommunications, and many others.

Nevertheless, more recently, different applications have also attracted the attention of academic and industrial researchers. In this case, the key features are represented by the mechanical properties of the electronics (large area and flexibility) and by the low-cost of the manufacturing process.

For this reason, new materials and deposition techniques suitable for cheap substrates, like paper, plastic foils and fabrics [1], have been investigated, which can be processed in ambient environment with potentially high throughput. Different technologies have been developed to realize a wide set of devices such as physical sensors [2–4], photo detectors [5], light emitters, plastic actuators [6] and general purpose flexible electronics [7]. Not all these components can be integrated on the same substrate and manufactured within the same process yet, but they share common

manufacturing techniques and materials, hence the way to a full integration can be discerned at the horizon.

Of course, these new technologies do not aim to replace silicon ICs in high performance applications. Indeed, due to the low temperature nature of the process and to the use of materials suitable for deposition from solution, the electrical performance of large-area electronics is typically much lower than standard silicon technologies. The mobility of organic and metal-oxide semiconductors is usually about three orders smaller than that in silicon; the intrinsic gain of these transistors is a few tens; often only p- or n-type device are available; TFTs typically suffer from poor uniformity, bias stress and aging, which affect the parameters of thin-film transistors increasing the deviation from their nominal values.

2.2 Applications

Applications exploiting cheap flexible substrates, and cheap manufacturing process, can be divided at first glance in two main groups: large-area applications and low-cost applications. The first one aims to a reduction of the cost per area, while the second one to a reduction of the cost per transistor/function.

2.2.1 *Large-area Applications*

In the last two decades, the major force driving the innovation around large-area electronics was the industry of flat-panel displays. For this sort of applications indeed, electronics need to be manufactured on a surface much larger than common semiconductor wafers in order to drive all the pixels composing the display. In this domain the most interesting technology from a commercial viewpoint is thus the one achieving lower cost per area, not the one achieving lower cost per transistor (Moore's law).

At the beginning, TFT technologies developed for this purpose used to exploit glass substrates and polycrystalline or amorphous silicon [8, 9] as semiconductors. When materials suitable for low-temperature deposition enabled the integration of circuits on foils, lots of new applications became possible.

In the sphere of display applications, technologies on flexible substrates can be used for portable devices due to their higher ruggedness compared to the standard silicon ones. For example, if the display backplane is manufactured on flexible substrates, the touch screen would not crack if the portable device is accidentally dropped on the floor or if someone seats on it. Also, plastic foils are much lighter than glass substrates: a very convenient feature not only for wide screen televisions, but also for music players, tablets, e-book readers and smartphones. One of the most successful combinations of flexible electronics for display backplanes with new light-emitting materials can be found in Active-Matrix Organic Light-Emitting

Diode (AMOLED) displays which can be used in bendable, rollable and foldable portable systems, achieving at the same time low cost, large area, high resolution and low power consumption [10].

The interaction between light and charge carriers in semiconductors can also be exploited in flexible lighting surfaces [11] and solar cells [12]. In the first case, the semiconductor is used to convert electrical power in photon emission, while in the second it converts light into electric current. The use of large-area technologies for these applications would considerably decrease the cost of materials, production and shipment. Solar panels manufactured with these technologies are lighter and rugged; moreover the disposal of old cells would be easier, safer and thus cheaper.

The integration of electronics with plastic polymers enables actuating surfaces as Braille displays [6]. A matrix of organic transistors, similar to a display backplane, is used for pixel addressing. A dielectric elastomer can be bent applying a certain bias voltage to create a Braille symbol. When the ionic polymer-metal composite (IPMC) strip is properly biased, the plastic hemisphere connected to its untied end is pushed against the top surface and can thus be read by the blind person.

Large-area electronics can also be employed together with many kinds of surface sensors, to enable sensing surfaces, like sheet-sensors [13], pocket scanners [14], and others [6, 13, 15–18]. For this sort of applications, mechanical flexibility plays a much more important role than TFT performance. For instance, surface pressure sensors on a bendable plastic foil that can be curved up to a radius of 2 cm were used to realize the first e-skin, providing tactile inputs to a human sized robot hand [19, 20]. Organic light sensors have also been used to realize a portable black & white scanner, where the matrix of light sensors along with their readout transistors was manufactured on a transparent bendable plastic foil. The light shining on the sheet-type scanner can either be reflected by the bright surface or absorbed by the dark colors. Functional peripheral organic ADCs (Analog to Digital Converters) could then be used to convert the current generated by the sensors in a grayscale digital picture.

All these applications give only a flavor of the potential use of large-area electronics on flexible foils. They show indeed how large-area electronics can interact in many different ways with both nature and human beings. It can sense different quantities, transmit electrical signals and irradiate light, and even provide mechanical actuation through dielectric elastomers.

2.2.2 Low-Cost Applications

Exploiting technologies suitable for large area, many kinds of sensors have been demonstrated, also beyond the domain of smart surfaces. Temperature, strain, chemical, and biomedical sensors [21] can also be used for ultra-low-cost applications like circuits integrated in packaging at item level. A unique process integrating sensors and electronics paves the way towards disposable smart sensors: systems aiming at the detection of a physical quantity and able to perform simple actions when required.

In these applications the electronic function becomes more important, since many building blocks need to be designed in order to process the sensor analog signal and make it amenable for post processing. Analog, digital and mixed-signal circuits must be designed based on technologies that are often superficially characterized, affected by large mismatch and process variations, and unstable under bias and environmental aggressions. Once these issues will be overcome with the help of circuit and technology solutions, we will witness e.g. smart sensors integrated in the package of food or pharmaceuticals to test their conservation quality, assays to monitor the level of bacteria in water, and robots equipped with conformable electronic skin [19] sensing roughness, softness, temperature and other qualities of our world.

Let us consider a smart sensor in the package of food. Every single item in a refrigerating room, or in the trailer of a truck, could detect locally its own temperature. This information could be used for instance to notify the final customer either if the desired product suffered multiple defrosts, or if it was perfectly stored and freshly delivered to the grocery shelf.

A chemical sensor integrated in a can of tomato sauce could reveal an excessive acidity and switch on an expiration LED. Or, in pharmaceuticals, it could monitor some excessive chemical levels in the medicine and communicate the automated storing system to withdraw the item from the market.

In order to perform such activities, the simplest smart sensor only requires a few building blocks (Fig. 1.2): a sensor, the sensor frontend, and a link to the base station that can perform more complex data processing and control more elaborated actions. In the following, the “sensor frontend” will be investigated.

The frontend chain begins with an analog signal conditioning interface: first, to reduce the impact of the noise introduced by the electronics on the weak input signal; second, to amplify the analog signal to a voltage range compatible with the data conversion. These operations are not trivial since the supply voltage of large-area electronics can reach several tens of volts and the intrinsic gain of the transistors is usually low. Moreover the lack of a complementary technology prevents the use of almost all the well-known architectures used in CMOS technology for operational amplifier designs. Indeed, the low intrinsic gain of TFTs makes negative-feedback systems design very challenging, hampering the effectiveness of linearity-enhancement and offset-reduction techniques.

The second step is the analog-to-digital conversion, required to achieve a robust data transmission to the base station. Also in this case, the poor performance of the electronics poses severe hurdles for the design of analog-to-digital and digital-to-analog converters. Even between closely-placed transistors, the process parameter variations and the large TFT mismatch reflect in significant offset at the input of e.g. comparators and OpAmps, hampering their use in ADC topologies like flash or pipelines. Only ADC architectures which are more resilient to comparator offset and exploit the relatively better matching of passives like SARs have been shown in literature, but even in this case the maximum linearity achieved was of about 5 bit [22]. When following oversampling and noise-shaping approaches, the designer has to deal with the low cut-off frequency of the organic transistors, which reflects

on a limited gain-bandwidth product in the OpAmps, so that the linearity achieved at the state of the art with these approaches is even lower [23].

Digital building blocks are also required in order e.g. to control the data flow, to restore signal synchronization, or to assist the data conversion. In this case, the limited static performance of the TFTs and the lack of complementary transistors affect the robustness of the digital circuits, resulting in a relatively high chance of non-functional circuits due to both hard and soft faults (i.e. errors due respectively to hardware faults like shorts and lines stuck at V_{DD} or gnd, or simply to excessive parameter variations). For this reason, the design of a robust digital logic is also mandatory.

Nowadays unipolar technologies are by far the most reliable in terms of hard faults and, for this reason, they provide the best solution for complex circuit design. However, with increasing process reliability, also complementary technologies will eventually offer similar hard-yield. At that point, soft faults will limit the maximum circuit complexity and unipolar technologies will need smart solutions to achieve yield levels comparable to the ones that can be achieved with complementary ones. This may still be interesting for practical applications, because of the far cheaper process that unipolar technologies enable.

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