Cambridge Elements

Organic and Amorphous-Metal-Oxide Flexible Analogue Electronics

Vincenzo Pecunia, Marco Fattori, Sahel Abdinia, Henning Sirringhaus, Eugenio Cantatore

Abstract: *Recent years have witnessed significant research efforts in flexible organic and amorphous-metal-oxide analogue electronics, in view of its formidable potential for applications such as smart-sensor systems. This Element provides a comprehensive overview of this growing research area. After discussing the properties of organic and amorphous-metal-oxide technologies relevant to analogue circuits, this Element focuses on their application to two key circuit blocks: amplifiers and analogue-to-digital converters. The Element thus provides a fresh look at the evolution and immediate opportunities of the field, and identifies the remaining challenges for these technologies to become the platform of choice for flexible analogue electronics.*

Keywords: flexible amplifiers, flexible analogue-to-digital converters, organic TFTs, amorphous-metal-oxide TFTs, circuit integration on foil

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1 Introduction

Recent years have witnessed significant research efforts in flexible organic and amorphous-metal-oxide analogue electronics. For a long while, academic and industrial actors focused primarily on the application of organic and amorphous-metal-oxide semiconductors to digital circuits, considering analogue circuits too challenging to implement. This was up until the concepts of smart-sensor systems and the Internet of Things gained momentum, leading to the realisation of the formidable potential of organic and/or amorphous-metal-oxide analogue electronics. While a couple of demonstrations of organic differential amplifiers were reported prior to 2010 [1], [2], the first systematic investigation of the scope of organic analogue electronics can be identified in the seminal work of Marien et al., which examined in detail organic unipolar amplifiers [3], [4] and reported the first organic delta-sigma analogue-to-digital converter (ADC) [5]. Amorphous-metal-oxide analogue electronics started off only a couple of years after (the first differential amplifier was reported by Tai et al. in 2012 [6]), partly due to the later development of the amorphous-metal-oxide-semiconductor technology.

These early works on organic and amorphous-metal-oxide analogue electronics evidenced the challenges of this area, and prompted the search for circuit-design, process, device and material strategies for higher circuit performance. Subsequent efforts have been rewarded with a number of breakthroughs. For instance, solution-processed organic and hybrid organic/amorphous-metal-oxide complementary differential amplifiers have now reached voltage gain figures above 40 dB [7], and in some cases even greater than 60 dB [8], and are capable of working

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down to a battery-compatible 5 V power supply [8]. Moreover, ADCs on foil have recently reached an effective resolution of 8 bits [9].

This Element arises from the need for a comprehensive picture of this growing research area, inclusive of the most recent breakthroughs and emerging directions. Prior to 2013, when the volume *Analog Organic Electronics* by Marien et al. was published [10], flexible analogue electronics had been explored almost exclusively in organic technologies of the unipolar kind. While specific aspects on subsequent developments were captured in a few later works (e.g., by Raiteri et al. [11], Abdinia et al. [12], and Sun et al. [13]), recent years have been particularly eventful, especially in the field of amorphous-metal-oxide and complementary organic/hybrid analogue electronics. This demands a fresh look at the area and a reassessment of its potential, both of which this Element pursues. In view of the multidisciplinarity of flexible analogue electronics, the authors recognise that this research domain is not only of interest to the specialists of analogue electronics and organic/amorphous-metal-oxide circuits, but also to the physicists, chemists and material scientists who, in fact, have contributed much to its development. Therefore, this work pursues both the details and their context, and strives to provide accessibility to non-specialists by also covering the more fundamental aspects of the field.

Before delving into the heart of the matter, it is worthwhile to expand on the motivations underlying flexible organic and amorphous-metal-oxide analogue electronics. After all, conventional analogue circuits, as produced via silicon technology, are commercially available off the shelf, and can meet an extremely wide range of functional demands with outstanding performance. More than that, digital electronics has long been dominant in flexible electronics, hence it is important to clarify for which applications it is useful to pursue organic and/or amorphous-metal-oxide analogue circuits. This discussion is the focus of the rest of this introductory chapter, which aids the reader to put in context this Element as a whole.

1.1 Analogue Electronics: An Interface to the Physical World

While the modern era has been dubbed the Digital Age due to the impact of digital electronics on our way of life, it is self-evident that the physical world is fundamentally analogue. The temperature and humidity in our homes, the oxygen content of our blood, the electrical pulses from our cells, for instance, all vary continuously within a given range. The interaction of our digital devices with the physical world is, therefore, mediated by analogue circuitry, whose role is to condition the informative content of the signals of interest so as to allow their reliable subsequent processing.

When dealing with quantities from the physical world, as transduced by sensors, electronics inevitably has to deal with the problem of amplification. This involves boosting the amplitude of a signal in order to prevent its corruption by electronic noise and interference. This function is best carried out in the immediate vicinity of the signal source (i.e., a sensor) so as to minimise the amount of interference that can be coupled, and to decrease the impact of the noise that is added by the signal conditioning chain.

Suitably amplified signals have to be converted into the digital domain prior to carrying out computation and further processing. This underlies the need for analogue-to-digital conversion. ADCs generate a digital representation of analogue signals exploiting together suitable analogue and digital circuitry. The analogue part of an ADC typically determines its performance in terms of accuracy, speed and energy efficiency.

In summary, amplification and analogue-to-digital conversion are two key functions to interface electronic devices with the physical world. Indeed, they are ubiquitous in sensing applications in which the acquisition of the transduced signals is to be combined with digital processing.

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1.2 Sensorisation and the Need for Mechanically Flexible Analogue Electronics

Conventional silicon-based analogue electronics has been typically allocated to silicon chips. Its development over the years has gone through the same miniaturisation trend (down to the ten nanometres of the recent technology node) that has characterised digital integrated silicon electronics.

While silicon-based analogue electronics has been dominant thus far, recent developments in the electronic industry and market have highlighted the need for alternative platforms for analogue electronics in specific applications. In particular, this concerns the demand for *sensorisation*, namely the addition of sensing capability to the objects and environments of our daily life. This capability has to cope with the multitude of quantities from the physical world to be captured and processed at once, and the variety of locations of the sensing elements involved. For the sake of illustration, a vision has emerged for the realisation of smart homes, which would have to be equipped with the ability to interact with all appliances in it and to provide for the residents' safety, comfort and entertainment. Situations such as this clearly surpass the conventional paradigm of star-connected sensor systems, which come with a centralised chip carrying out all the electronic functions, while sensors merely convert the physical quantities of interest into electric signals. This approach is obviously not viable when the number of sensors to be interconnected becomes large, as the system would be burdened, for instance, by bulky wiring, and by substantial interference along the path from the sensors to the electronics.

Sensorisation thus leads to a new paradigm for analogue electronics, which generally goes by the name of smart-sensor systems. As the word suggests, one such system would integrate a manifold of sensors, and each of them would have to come with electronic functionality (hence their attribute *smart*). In particular, besides the transduction element (e.g., a photodiode for an optical smart sensor), a smart sensor would have to include a

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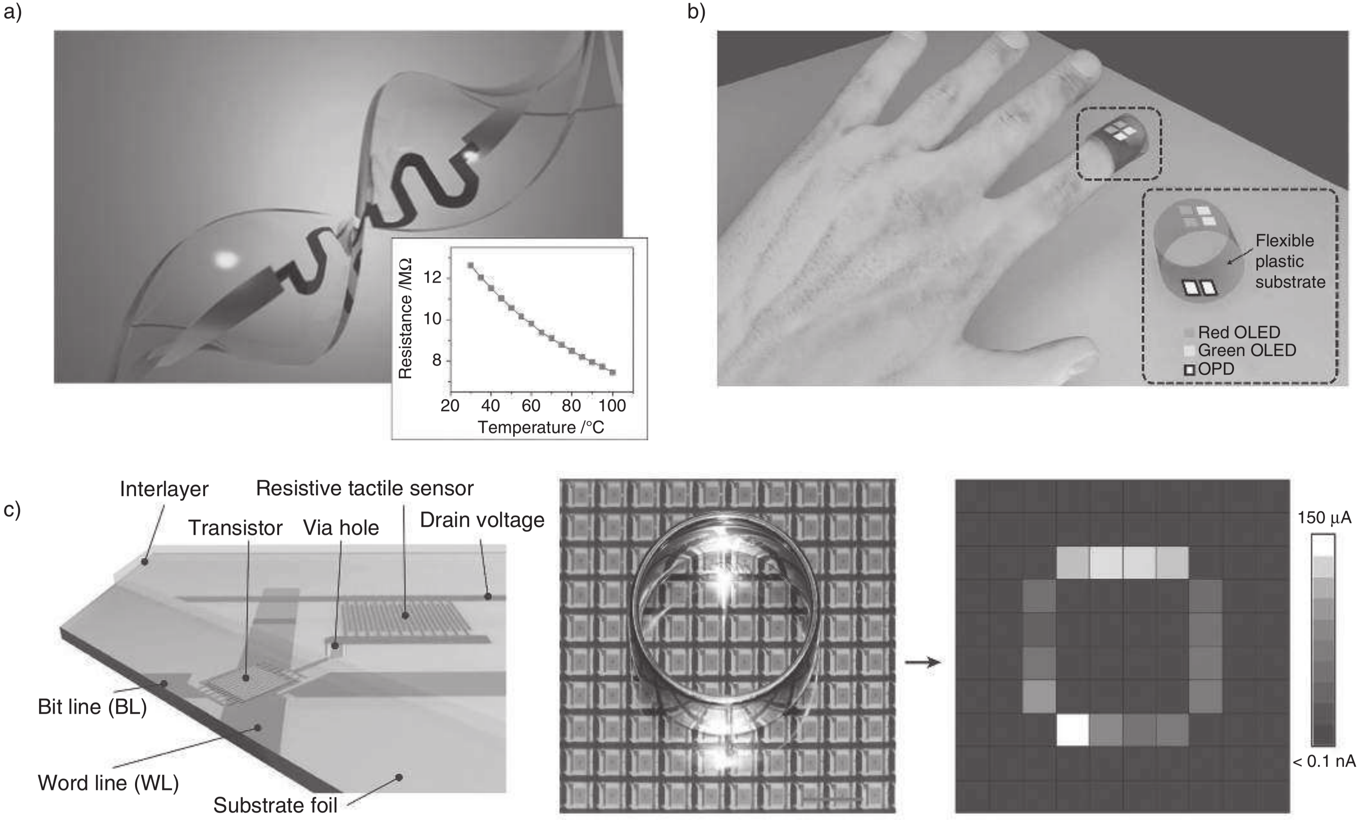
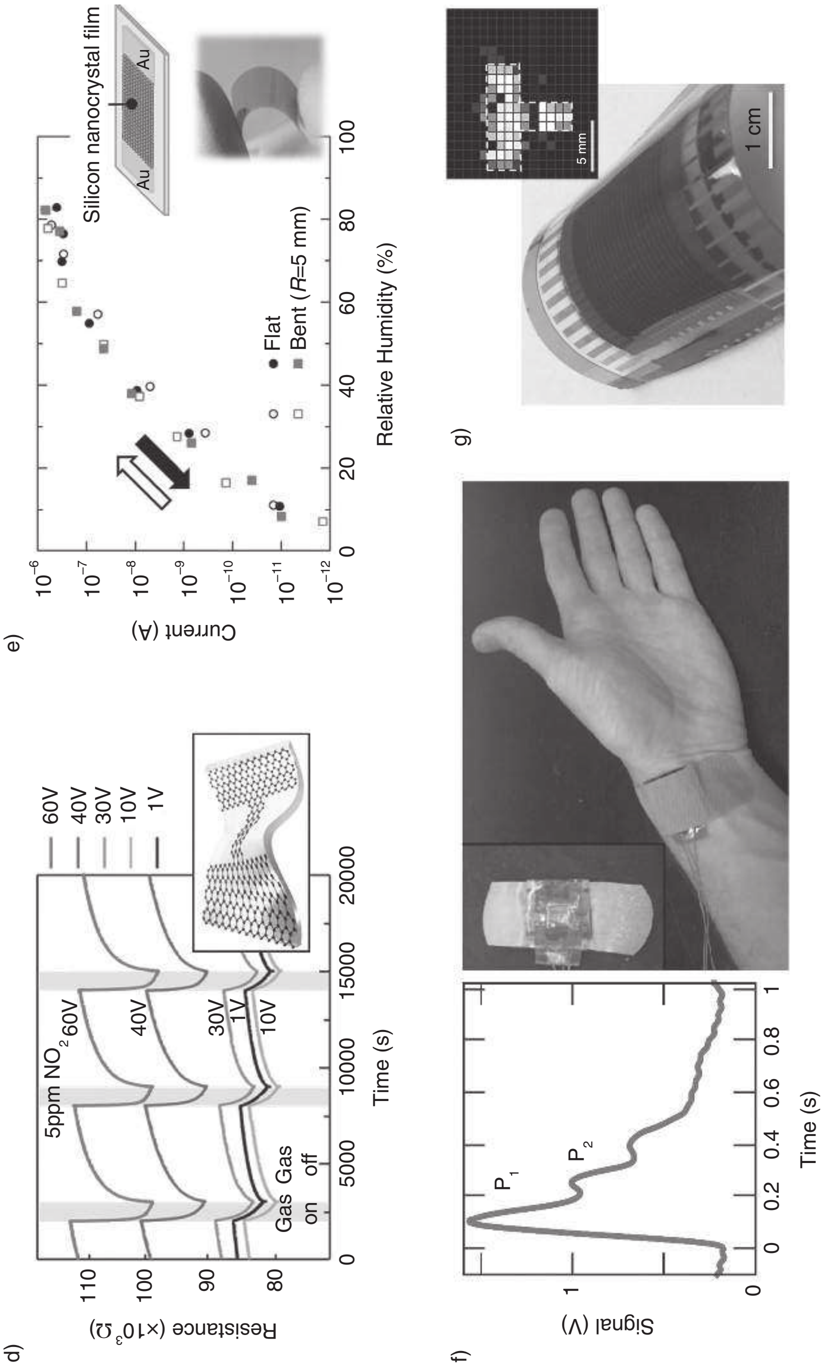
dedicated analogue interface (e.g., a preamplifier), an ADC, data transmission capability and a power supply [14]. This would enable a modular sensing system that eliminates the complexity and unfeasibility of a star-connected scheme. Finally, smart-sensor systems are an integral part of a broader technological revolution currently under way, that of the Internet of Things. According to this vision, smart sensors and distributed computing would all be interconnected seamlessly through an Internet-like network [15], [16]. Hence, the information acquired from smart sensors disseminated in the objects and environments of our daily life would be available to us in real time, allowing us to make more informed decisions.

Smart-sensor systems require the analogue electronics embedded in them to be deployed in unique form factors and environments – for instance, on clothes, on packaging, on our skin – and, at the same time, to be produced through a cost-effective technology. Only an analogue electronics technology on foil would be able to address these demands. Realising smart sensors on plastic foil would ensure their flexibility, conformability, light weight and robustness, all properties that are needed to disseminate sensors unobtrusively in the objects and environments of our daily life. Furthermore, flexible electronics naturally lends itself to high-throughput manufacturing, such as roll-to-roll fabrication, thus potentially enabling a cost-effective deployment of smart sensors. It is thus apparent that the success of sensorisation and smart-sensor systems can be enhanced and extended by the availability of technologies for analogue circuit fabrication on lightweight and mechanically flexible substrates.

It is noteworthy that the push for sensorisation has driven a large research effort in mechanically flexible sensors, which points to the attractive opportunity of integrating sensors and analogue circuity on the same flexible substrate. Indeed, over the past couple of decades, a large number of reports have appeared on flexible sensors capable of responding to a wide range of stimuli, for instance: light [17]–[19], humidity [20]–[22], temperature [23]–[26], pressure [25], [27]–[29], gas/vapour concentration [30]–[33]


a)
Resistance /MΩ
12
10
8
20
40
60
80
100
Temperature /°C
b)
Flexible
plastic
substrate
Red OLED
Green OLED
OPD
c)
Interlayer
Resistive tactile sensor
Transistor
Via hole
Drain voltage
Bit line (BL)
Word line (WL)
Substrate foil
150 μA
< 0.1 nA


d)
Resistance (×10^3 Ω)
80
90
100
110
Time (s)
0
5000
10000
15000
20000
5ppm NO$_2$
60V
40V
30V
1V
10V
Gas on
Gas off
60V
40V
30V
10V
1V
e)
Current (A)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Relative Humidity (%)
0
20
40
60
80
100
Flat
Bent (R=5 mm)
Silicon nanocrystal film
Au
Au
f)
Signal (V)
0
1
Time (s)
0
0.2
0.4
0.6
0.8
1
P$_1$
P$_2$
g)
5 mm
1 cm

Caption for Figure 1.1 (cont.)

Figure 1.1 Examples of sensors on foil. a) Graphene thermistor on stretchable foil. The plot in the inset shows the changes in resistance with temperature. Adapted with permission from [26]. Copyright 2015 American Chemical Society. b) Pulse oximetry sensor based on organic light-emitting devices and organic photodetectors. The devices are integrated onto a flexible and lightweight finger band. Reprinted with permission from Macmillan Publishers Ltd: Nature Communications ([37]). Copyright (2014). c) Organic-based active-matrix tactile sensing foil. (from left to right) Pixel structure, comprising a resistive tactile sensor and a switching transistor; photograph of a metal ring placed on the sensing foil; corresponding pixel current over the sensing foil. Adapted with permission from Macmillan Publishers Ltd: Nature ([27]). Copyright (2013). d) Flexible graphene gas sensor. The sensor is realised on plastic foil, and both its electrodes and sensing area are made of graphene (see inset). The plot depicts the sensor resistance over time at variable applied voltages in response to consecutive pulses of NO_2 gas. Adapted with permission from [33]. Copyright 2015 American Chemical Society. e) Flexible nanocrystal-based humidity sensor. The plot depicts the sensor current at variable humidity levels. The insets show a schematic of the sensor architecture and a photograph highlighting its flexibility. Adapted with permission from [22]. Copyright 2017 American Chemical Society. f) Pressure-sensing foil based on polymer transistors for the measurement of pulse waves of the radial artery. (from left to right) Signal recorded from a volunteer’s wrist; photograph of flexible sensor mounted onto volunteer’s wrist. Adapted with permission from Macmillan Publishers Ltd: Nature Communications ([28]). Copyright (2013). g) Flexible imager for the detection of visible light/X rays. The imager comprises organic photodetectors and carbon nanotube transistors. The inset shows the photocurrent response across the imager under illumination through a T-shaped shadow mask (see dashed line). Adapted with permission from [38]. Copyright 2013 American Chemical Society.

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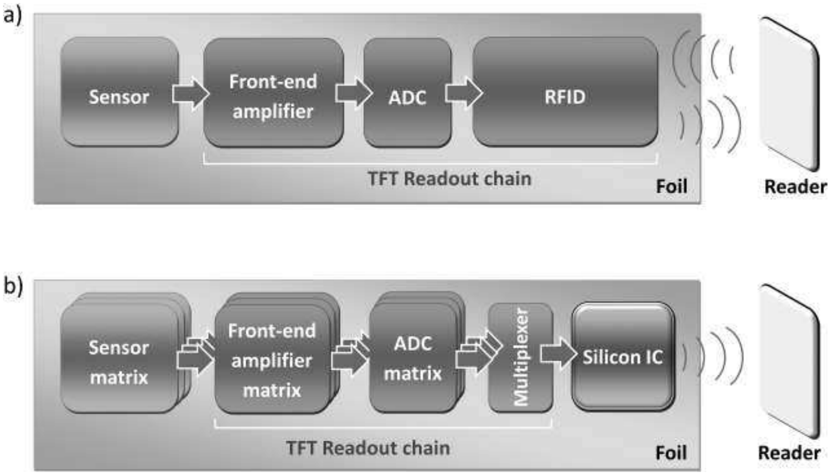

Figure 1.2 Two possible implementations of smart-sensor systems on foil. a) Sensor-augmented flexible RFID tag. b) Hybrid integration on foil of a sensor matrix readout chain and a silicon IC.

and biosignals or bioanalyte concentration [34]–[36]. A few impressive demonstrations of flexible sensors are presented in Figure 1.1, which provides an immediate visual indication of the formidable potential of flexible smart-sensor systems for manifold applications.

The block diagrams of two possible implementations of flexible smart-sensor systems are depicted in Figure 1.2. Figure 1.2a shows a sensor-augmented radio-frequency identification (RFID) tag in which all circuits are implemented using thin-film transistors (TFTs) on foil. The sensor translates an environmental parameter such as temperature into an analogue signal, which is then boosted through an amplifier and converted to digital form using an ADC. The resulting digital code is sent through a radio link to a reader, which powers the sensor system through the radio link.

The system in Figure 1.2b includes hybrid integration between electronics on foil and a silicon integrated circuit (IC). The