Overview of the EC Project FLEXIBILITY: Organic and Thin-Film ICs up to Radio Frequencies for Multifunctional Flexible Systems

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***Abstract*—This paper provides an overview of the research activities within the frame of the European project FLEXIBILITY. The project aims at advancing the competitiveness of Europe in the area of multifunctional, ultra-lightweight, ultra-thin, bendable organic and large area electronics (OLAE). An overview of the technologies available to the consortium is provided, together with details of the performance achieved by the first prototypes. Particular focus is given to the circuit design in technologies compatible with the flexible components and systems. Using a $50\,\mathrm{MHz}$ IGZO TFT technology, several circuits have been demonstrated, including a $20\,\mathrm{MHz}$ AM demodulator.**

***Index Terms*—OLAE, OFET, IGZO TFT, flexible radio.**

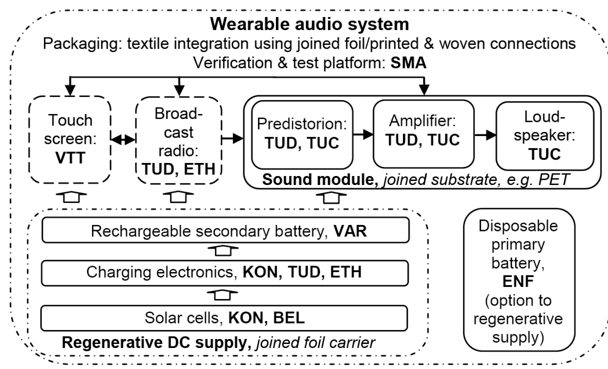

Fig. 1. The wearable audio system is an example of complex multifunctional system considered in FLEXIBILITY . It consist of several integrated functional modules, including a broadcast radio receiver and a sound module with driving electronics. All components are mechanically flexible.

I. Introduction

The European Commission (EC) project FLEXIBILITY [1] aims at advancing the competitiveness of Europe in the area of multifunctional, ultra-lightweight, ultra-thin, bendable organic and large area electronics (OLAE). With OLAE, technology systems can be fabricated on a simple piece of plastic foil or even paper resulting in low fabrication costs per area. The research efforts combine the complementary competencies of four large companies, three SMEs, one research institute and three universities. Involved countries are Austria, Finland, Germany, Italy, Greece and Switzerland. The FLEXIBILITY consortium has access to a very heterogeneous set of flexible technologies suitable to provide a wide range of functions of interest for complex electronic systems: disposable and rechargeable batteries, organic printed transistors, flexible thin-film transistors, printed motion and temperature sensors, printed OLEDs and touch screens, textile integration technology. The project aims at designing fully flexible multifunctional systems, integrating components with functionalities from all those different areas in packaged flexible substrates or integrated into wearable textile systems. The core goal of the project is to further develop all the available technologies to enable their integration into flexible or wearable systems, making them mechanically, electrically and functionally compatible each with all others. In the planning phase of the project, three of such systems have been proposed for demonstrating the potential of the consortium technologies [2]: (a) textile integrated audio module with integrated broadcast radio and solar supply; (b) active receiver tag for wireless streaming of audio data and advertising; (c) security tag system with acoustic alarm, motion or temperature sensors. The architecture of the audio module with broadcast radio receiver is shown in Fig. 1. The system consists of several integrated functional modules, including a broadcast radio receiver and a sound module with driving electronics; all components are mechanically flexible.

For the realization of these systems, the features of several low-cost flexible OLAE technologies are combined. R2R printing will be employed for components requiring large areas (e.g. loudspeaker, high-power audio amplifiers and solar cells), 3-D integration, as well as integration of heterogeneous devices on one single substrate. Compact (down to $10\,\mu\mathrm{m}$ gate length), fast ($>200\,\mathrm{MHz}$ transit frequency, mobilities $>10\,\mathrm{cm}^2/\mathrm{Vs}$), low-loss IGZO (Indium Gallium Zinc Oxide) thin-film technology [3] will enable wireless communication systems. To enable efficient circuit development in standard

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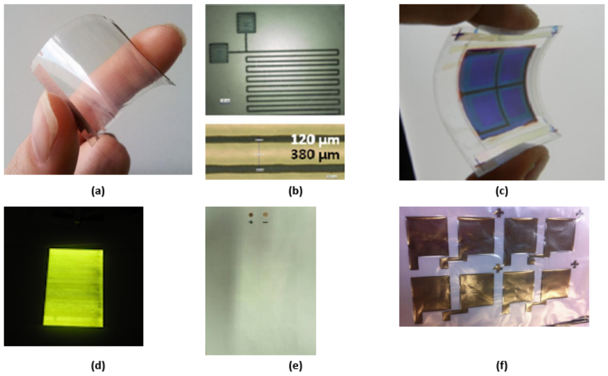

Fig. 2. Examples of printed and flexible devices and sensors fabricated by FLEXIBILITY partners: (a) 5 cm^2 speaker; (b) resistive temperature sensor; (c) organic photodiode for motion detection; (d) a 6 cm^2 organic LED; (e) 24 V disposable battery; (f) 24 V rechargeable battery

CAD tools possible, design-kits including scalable models and automated layout templates are developed. Interface and packaging issues are studied for full system integration on a common flexible foil enabling bending radii down to 1 cm.

II. Flexible Components and Circuits

Within this frame of technology development, several flexible devices and components have been successfully fabricated. A number of versions of flexible printed speakers (Fig. 2(a)) were fabricated and tested: maximum sound pressure levels of 80 dB were demonstrated [4] with 50 V_{PP} signals, but useable levels can also be achieved at 10 V_{PP}. Materials and tools for printed resistive sensors (Fig. 2(a)) have been evaluated: Ag-based inks, curable at just 150 °C, yield linear dependence of resistance in the target range of $10 - 70$ °C. The first organic photodiodes (OPDs) on flexible substrates have been fabricated and will serve as motion sensors (Fig. 2(c)); based on spray-coated photosensitive devices, the sensors are already capable of detecting light in the visible and near-infrared regime with a wavelength up to 800 nm. The development of several version of roll-to-roll (R2R) printing of organic light-emitting diodes (OLEDs, Fig. 2(d)) has been carried out with maximum luminance in the order of 200 $\mathrm{cd/m^2}$. Disposable flexible batteries for 24 V (Fig. 2(e)) have been successfully manufactured with R2R printing and lamination equipment; the high voltages are achieved by series connection of multiple 1.5 V cells. Rechargeable batteries for the same supply voltage (Fig. 2(f)) were developed relying on the series connection of Nickel-Metal hydroxide cells, all printed in one sheet.

Two transistor technologies have also been improved for the target applications. R2R printed OFETs were demonstrated and are capable of transit frequencies (f_t) in the order of 70 kHz. For radio-frequencies applications, an IGZO TFT technology is available with f_t in the order of 50 MHz. Fig. 3 shows photographs (left and center) of a 1 µm IGZO TFT device. The current gain as a function of frequency is shown on the right-hand side of the figure, where an f_t of 47 MHz is extrapolated.

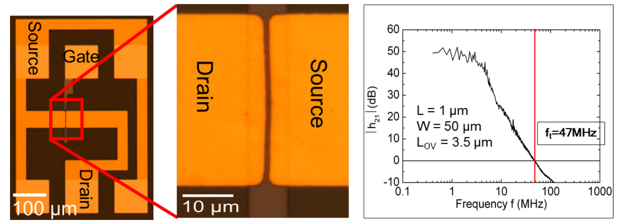

Fig. 3. Photographs (left and center) of a 1 µm IGZO TFT device. The current gain as a function of frequency is shown on the right-hand side of the figure, where an f_t of 47 MHz is extrapolated.

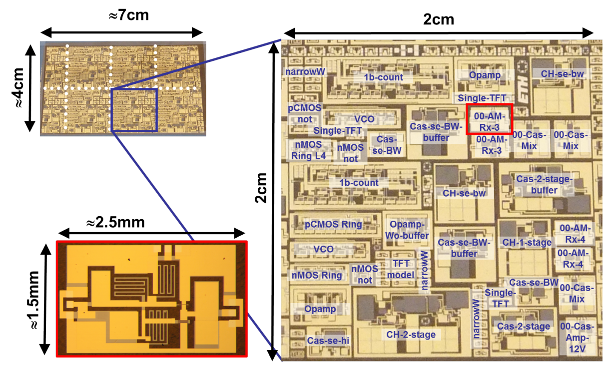

Fig. 4. Photograph of fabricated a-IGZO TFT circuits. The shown 4 cm^2 are is populated with more than 20 circuits, including VCOs, amplifiers, inverters, mixers; the bottom-left cutout shows the detail of an AM demodulator.

Fig. 4 shows several replicas of a 4 cm^2 layout. This, in turn, is populated with more than 20 circuits, including VCOs, amplifiers, inverters, mixers; the bottom-left enlarged cutout shows the detail of an AM demodulator, fabricated on a 1.5x2.5 mm^2 area. The operation of this circuit relies on a half-wave rectifier and is capable to demodulate AM signals on carrier frequencies up to 20 MHz.

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