High Performance Flexible Electronics for Biomedical Devices

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***Abstract*— Plastic electronics is soft, deformable and lightweight and it is suitable for the realization of devices which can form an intimate interface with the body, be implanted or integrated into textile for wearable and biomedical applications. Here, we present flexible electronics based on amorphous oxide semiconductors (a-IGZO) whose performance can achieve MHz frequency even when bent around hair. We developed an assembly technique to integrate complex electronic functionalities into textile while preserving the softness of the garment. All this and further developments can open up new opportunities in health monitoring, biotechnology and telemedicine.**

I. INTRODUCTION

Integrated circuits development started out in the 60s with primarily utility and industrial applications where large boxes of electronics and storage systems were designed for computational tasks. As result of device miniaturization, electronics has become smaller and smaller with more advanced functionalities and it no longer occupies large space on the desk but it can fit in a hand or a pocket [1]. However, silicon chips are still rigid, bulky and brittle. They are perfect to be hold in hand but what if you want to wrap the brain with them? What if you want to put them on the skin to achieve an intimate interface with the body?

In the early 1990s, a completely different class of electronics emerged to meet a need that was impossible to address with silicon wafer technology: active matrix circuits for switching pixels in liquid crystal displays. From flexible displays, the scope has expanded to include more compelling and more technically challenging opportunities in biomedical devices which are minimally invasive and which can be worn or implanted. To meet these requirements new design strategies, materials and fabrication schemes have to be considered and investigated. Here, mechanical engineering is as important as circuit design and curvilinear, ergonomic, or biologically inspired layouts are often exploited as alternative to more standard approaches [2-4]. However, flexible electronic circuits still remain at the heart of any flexible system and their performance and fabrication schemes usually define applications and costs.

This paper provides a general overview of materials and technologies for flexible electronics. The focus is on devices and circuits which are fabricated directly on polyimide foils and based on amorphous Indium Gallium Zinc Oxide (a-IGZO) and high-k dielectric. Section III shows an original approach to integrate electronics into textiles which can be used in medical applications. Finally, flexible electronics on very thin and biocompatible substrate offers unprecedented bending radii, conformability and lightness, all attributes which are important for smart-skin, tissue sensing and implantable devices.

II. THIN FILM TECHNOLOGY

A. Transistors

The transistor is the basic building block of any digital and analog circuit. In particular, analog amplifiers are essential for sensor readouts and transceivers. Transconductance, g_m, output resistance, $1/g_{ds}$, gate capacitance, C_G, and transient frequency, f_T, are the most common features of merit to evaluate the device AC performance. Flexible thin film transistors (TFTs) can be fabricated by using organic materials [5], silicon nanowires [6] or nanomembranes [4] or amorphous oxides like a-IGZO [7]. The latter choice, combined with direct fabrication on foil, offers the possibility of large area processing (RF sputtering and roll to roll technology) and good electrical mobility, μ_{eff}, (>10cm^2/Vs) and, hence, constitutes a good compromise between cost and performance. To target radio-frequency (RF) operation the device must have short channel length and it must be optimized in terms of overlapping capacitance and contact resistance [8, 9]. This sets challenges for the design, the processing and the materials (Figure 1).

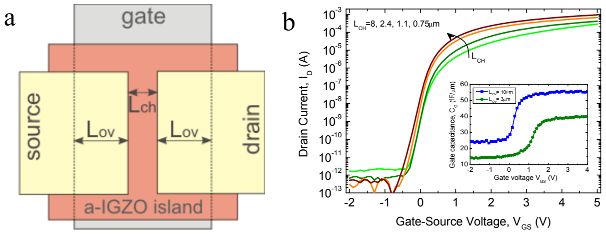

Figure 1- Thin film transistors are fabricated directly on kapton foil by using low temperature processable materials (a-IGZO by sputtering, Al_2O_3 by ALD, Cr/Au by e-beam evaporation), standard UV lithography and etching processes. (a) Top view of a typical device layout illustrating the most important geometrical parameters (L_{OV}=Overlapping length between gate and drain /source, L_{ch}=channel length, W=channel width). (b) Transfer characteristic of 4 devices with different channle length. The inset shows the capacitance change for different L_{OV}.

We optimized self-alignment lithography which enables the shrinking of the channel length (<1μm) and the minimization of the overlapping area between source/drain and gate regions (Figure 2). This leads to devices which have a transient frequency above 100MHz [10] and which can be used in RF applications. Such devices are directly fabricated on 50μm thick Kapton foil and continue to work even when

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bent down to radii of 3.5mm (ε≈0.7%). The strain can be applied either parallel or perpendicular to the channel. In both cases high strain level (ε >0.7%) induces cracks in the device but in the former case they short circuit source and drain and permanently compromise the device to operate properly (Figure 3). Such mechanical constraints provides design guidelines which are particular important when dealing with circuits [11].

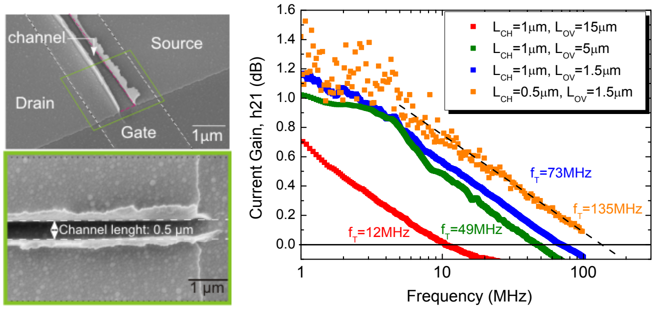

Figure 2- SEM picture of a TFT with 0.5µm long channel. Process optimization (self-alignment) can lead to TFTs with channle length smaller than 1µm with a remarkable advantages in terms of operating frequency.

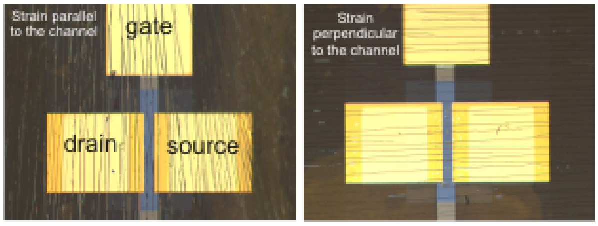

Figure 3- Cracks into TFTs in case of parallel and perpendicular strain to the channel.

B. *Circuits*

In any real application biometric or environmental signal must be filtered, amplified and transmitted. All these operations require analog circuits [12, 13]. Here, we present an example of operational amplifier fabricated directly on kapton foil and constituted by 16 a-IGZO based TFTs [14]. The circuit has a total area of 2.5mm x 1mm and it operates at a supply voltage of 5V with an equivalent power consumption of 900µW (Figure 4). The gain is about 19dB and the gain-bandwidth product is about 470KHz. The circuit continues to work even when bent down to radii of 5mm (ε≈0.5%).

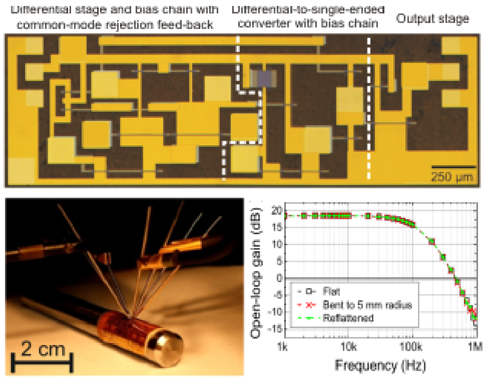

Figure 4- Operational amplifier fabricated by thin film technology. The circuit consists of 16 TFTs and works even when bent down to 5mm with an open loop gain of 19dB up to a frequency of 100KHz.

III. FLEXIBLE ELECTRONICS INTO TEXTILE

One of the most promising emerging fields in wearable systems is the convergence of electronic components and textile. Within the field of wearable computing, smart textile applications range from medical monitoring of physiological signals, including heart-rate, guided training, and rehabilitation of athletes, to assistance for emergency first responders, and to commercial applications integrated into everyday clothing. The simplest scheme to integrate electronic into textiles consists in using off-the-shelf components which need to be placed on a substrate or support and then woven or simply attached onto the fabrics. This approach offers rich electronic functionalities but pose concerns regarding the comfort and the wearability. To maintain essential textile properties, smart textiles are evolving to integrate more electronic functions at the fiber level, but most fibers are limited to a single functionality. A third route consists in combining thin film flexible electronic devices including sensors and transistors, interconnect lines, and commercial integrated circuits with plastic fibers (e-fibers) that can be woven into textiles using a commercial manufacturing process [15]. Figure 5 shows how electronic fabricated on kapton foil can be cut into stripes and weaved into fabrics.

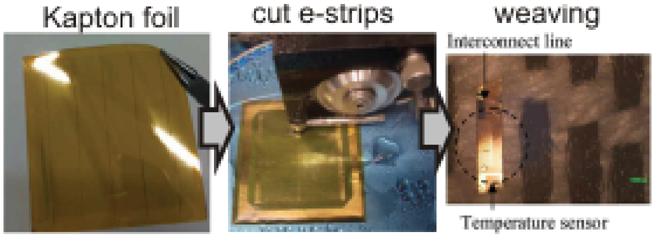

Figure 5- Process scheme to integrate electroncis into textile. Electronic devices are first fabricated on kapton foil which are subsequently cut into strips and weaved into the fabrics. Such approach allow to achieve reletively high functional complexity and preserve the textile bendability and softness and hence comfort.

Following this approach we realized a near infrared spectroscopy system (NIRS) fully integrated into a textile which can be wrapped around harm and shoulder of a patient and serve to monitor blood oxygen saturation by measuring backscatter light intensity [16]. The NIRS system consists of thin film devices fabricated on foils and off-the-shelf components which are attached on the plastic strips. Two light emitting diodes (LEDs) with wavelength of 760nm and 870nm, respectively are placed on a flexible plastic stripe close to each other. The current of both LEDs is controlled with a transistor which is as well located on the flexible plastic stripe. To detect the light which is back-scattered by the hemoglobin in biological tissue, a photodiode in conjunction with a transimpedance amplifier are mounted on a second flexible plastic stripe. LEDs, transistors, photodiodes and amplifiers were mounted on the flexible strips using standard micro-fabrication techniques such as wire bonding, soldering and gluing (Figure 6).

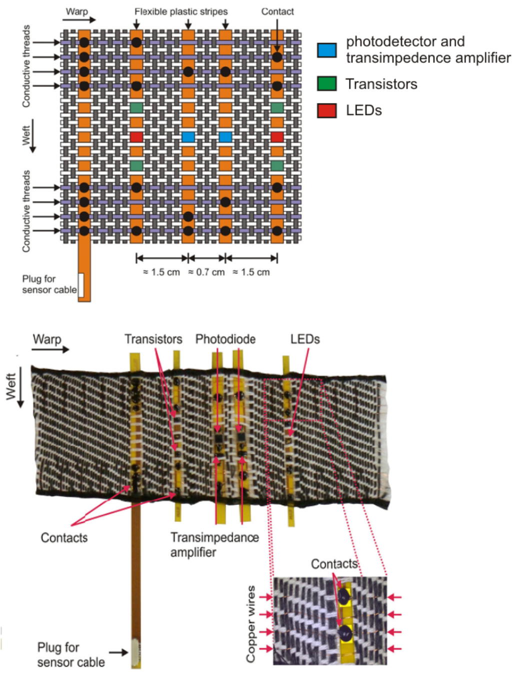

Figure 6- Woven sensor textile with flexible plastic strips in weft direction carrying LEDs, transistors, photodiodes and transimpedance amplifiers. In the inset, woven copper wires in warp direction are visible together with two encapsulated contacts between copper wires and contact pads on a flexible strip.

To test the electrical functionality of the textile integrated NIRS, the textile is connected to a custom made read-out and control board. This board pulses the LEDs with a frequency of 100Hz and a duty cycle of 10%. Simultaneously the board samples the voltages of the photodiodes and sends the data to a computer using a USB connection.

Placing the palm of the hand or a finger on the textile and thereby covering the LEDs and photodiodes, the pulse can be detected in correspondence of the heartbeat. The varying baseline is caused by movements of the hand which changes the light coupling efficiency between LEDs/skin and skin/photodiode. Additionally, tissue oxygen saturation (StO_2) and arterial oxygen saturation (SpO_2), change in oxygenated (ΔO_2Hb), in deoxygenated hemoglobin (ΔHHb) and in total hemoglobin (ΔtHb) can be also calculated (Figure 7).

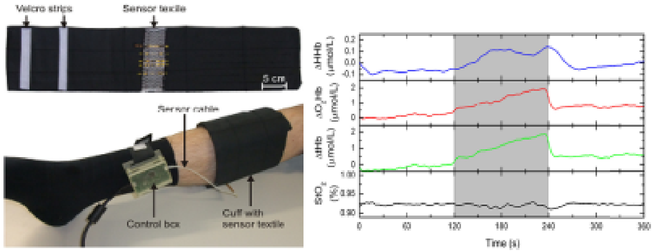

Figure 7- The sensor textile is sewn into a textile cuff together with Velcro strips for attaching to the human body. The cuff is strapped to the calf together with the control box. Between the control box and the cuff, the sensor cable is visible. Venous occlusions were performed on the calf for 2 minutes (marked in grey). During the occlusion, the HHb, O_2Hb and tHb concentrations did increase while the tissue oxygen saturation StO_2 stayed constant.

IV. THIN AND ULTRA-FLEXIBLE ELECTRONICS

To achieve more compliant electronics and target more compelling applications like smart-skin and implantable devices a bending radii of millimeters is sometimes not enough. Very recently, ultra-flexible electronics have been achieved on very thin substrates [2, 17, 18]. In addition to extreme bendability this approach provides also lightness and conformability which are important attributes to achieve intimate interface with human body or biological tissues. We developed a methodology which allows the realization of ultra-flexible electronics which can be potentially transferred onto any arbitrary organic or inorganic surface. The concept behind our scheme is illustrated in Figure 8.

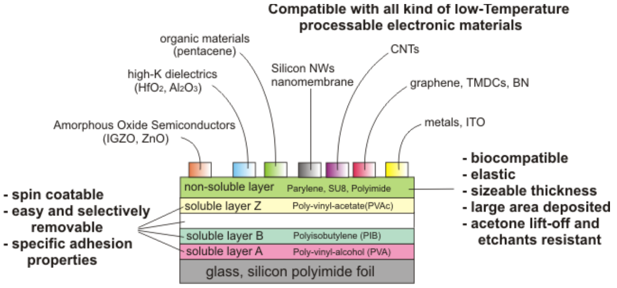

Figure 8- The proposed engineered substrate consists of several soluble films and of a non-soluble layer deposited on rigid or flexible support. The selective dissolution of the layers enables the release, the transfer, the adhesion and the removal after use of the electronics. The desired requirements for the layers are listed in bold and a set of possible materials is also provided. Low temperature processable materials can be employed to fabricate ultraflexible devices in electronics and photonics.

Several polymer films can be deposited by spin coating on a rigid or flexible support. Each of them should be easily and selectively removable by a specific solvent, while some could have specific properties like good adhesion. On top of the stack lays a non-soluble layer which constitutes the ultimate substrate film and which is released from the support after the dissolution of soluble layers. Depending on the applications, it can be chosen to be biocompatible, elastic and its thickness tuned to set the desired final flexibility. It must be resistant to the solvents which dissolve the underlying stack and possibly to acetone and etchants used for the structuring of the active electronic layers. Figure 9 shows a two inches wafer on which we implemented our method. After the dissolution of the soluble layers the electronics laying on a 1µm parylene membrane can be transferred onto human skin, plant leaves or onto textiles [18]. The very thin substrate confers extreme flexibility and conformability to the electronics which continue to work even when bent around human hairs with a radius of about 50µm (Figure 10).

The membrane is also light, transparent and biocompatible. The fabrication of transparent electronics enables the transfer on plastic contact lenses which can monitor biometric parameters as the intraocular pressure for Glaucoma diagnosis (Figure 11). The development of such technology could offer significant advantages over existing solutions in terms of thickness, lightness and transparency and, hence, comfort for the patient.

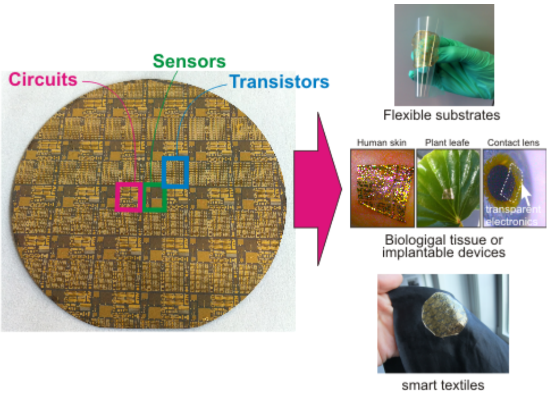

Figure 9- The scheme presented here enables the fabrication of ultraflexible electronic components which can be transferred onto any organic/inorganic surfaces including skin, plant leaves and textiles. The picture on the left shows a 2’’ wafer after the fabrication and before the membrane release.

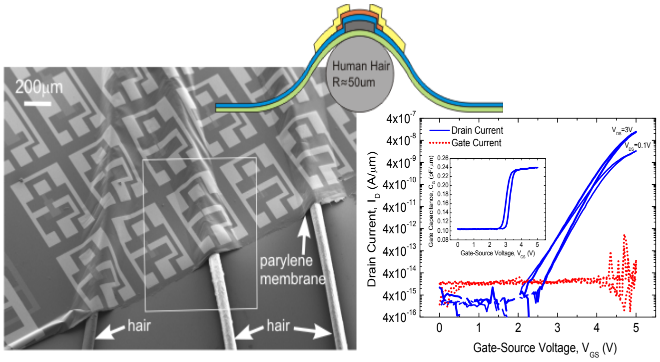

Figure 10- The very thin parylene membrane ensures extreme flexibility. This is experimentaly demonstrated by measuring transistors which continue to function even when wraped around human hairs with a radius of 50µm . We show the transfer characteristics of a transistor (W/L=280 µm /80µm) whose gate is wraped around the hair.

V. CONCLUSION

In this paper we described different forms of soft electronics, i.e. when fabricated on plastic foil, on very thin biocompatible substrate and when woven into garments. The materials we employed in the fabrication are compatible with low temperature processing and enable large area integration. Mechanical and electrical performance fit the requirements for radio frequency biomedical devices which can serve for health monitoring or telemedicine. Examples include smart contact lens carrying electronics which can monitor the intraocular pressure for glaucoma disease or a textile based near infra-red spectroscopy system to measure oxygen saturation.

Real devices, however, requires further developments in terms of system integration and engineering. Power delivery and wireless communication schemes are key requirements for useful systems and practical and efficient strategies have not been implemented yet.

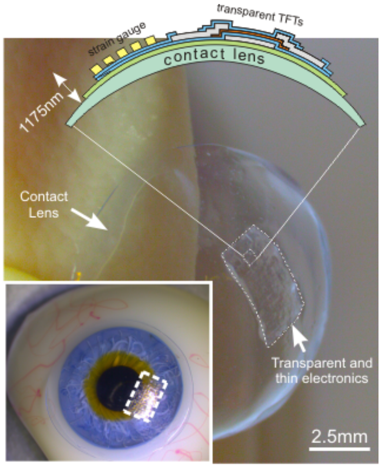

Figure 11- Thin and transparent electronics mounted on a plastic contact lens. Such device could be used to sense intraocular pressure to diagnose Glaucoma. Real system would require the development of wireless powering and communication scheme for data telemetry.

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