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A System-on-Chip and Paper-based Inkjet Printed Electrodes for a Hybrid Wearable Bio-Sensing System

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Abstract— **This paper presents a hybrid wearable bio-sensing system, which combines traditional small-area low-power and high-performance System-on-Chip (SoC), flexible paper substrate and cost-effective Printed Electronics. Differential bio-signals are measured, digitized, stored and transmitted by the SoC. The total area of the chip is 1.5 × 3.0 mm^2. This enables the miniaturization of the wearable system. The electrodes and interconnects are inkjet printed on paper substrate and the performance is verified in *in-vivo* tests. The quality of electrocardiogram signal sensed by printed electrodes is comparable with commercial electrodes, with noise level slightly increased. The paper-based inkjet printed system is flexible, light and thin, which makes the final system comfortable for end-users. The hybrid bio-sensing system offers a potential solution to the next generation wearable healthcare technology.**

I. INTRODUCTION

Biological information sensing plays an important role in clinical and healthcare applications. The traditional electrode technology commonly used in clinical or research fields is nonintrusive adhesive silver/silver chloride (Ag/AgCl) electrode. Some problems arising from using traditional wet electrodes are cable tangling, reduced comfort, and signal degradation due to dehydration [1].

In recent years, many attempts have been made to improve the traditional electrode technology [2 - 4]. Some researchers use fabric-based dry electrodes and get comparable results with traditional ones [4]. However, in order to make sure the electrodes efficiently contact with human body, tight clothes are needed during the monitoring, which is uncomfortable, especially for the elderly in continuous long-term monitoring. Today's medical devices still desire an efficient bio-sensor system which is ideally free of cumbersome cables, small, comfortable and low-cost [5].

Based on these considerations, we propose a hybrid paper-based inkjet-printed bio-sensing system embedded with a mixed-signal System-on-Chip (SoC). Compared with traditional circuits made up of off-the-shelf components, the SoC offers a tiny-size solution with high-performance and low-cost to fulfill the functional requirements. A paper substrate is used since it is cheap, printable, flexible (wearable), light and thin [6]. Inkjet printing is one popular printing technique in fabrication of printed devices [7]. Utilizing additive manufacturing process by digital inkjet printing in pattern fabrication removes the need for masks and etching steps, avoids material-waste, and makes it easy to apply customized bio-sensing electrodes and pattern according to a specific requirement [8]. Its Roll-to-Roll compatibility allows mass production and therefore is cost-effective. Due to its accurate alignment and non-contact features, inkjet printing can also be used to realize interconnection which combines the traditional silicon-based chip and printed electronics, and forms the hybrid system [9, 10]. In this paper, inkjet printing technology is applied for paper-based electrodes fabrication and a silicon-based chip is customized for printed electrodes. The performances are verified in *in-vivo* tests. A hybrid and wearable bio-sensing system is proposed.

II. HYBRID WEARABLE BIO-SENSING SYSTEM

The architecture of hybrid wearable bio-sensing system is shown in Fig.1, with an application scenario of ECG measurement. The hybrid system seamlessly integrates printed electronics with traditional silicon based electronics, taking advantages of both [10].

The SoC is fabricated in a 0.18-µm standard CMOS technology. It is less power consuming (20 µW from a 1.2 V

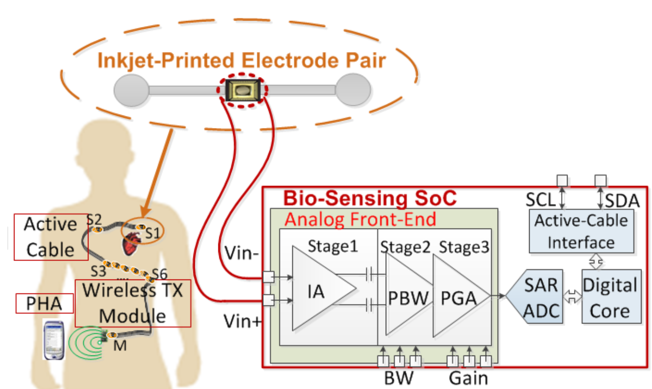

Fig. 1. A hybrid wearable bio-sensing system with an application scenario of ECG measurement.

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supply) compared with low-power off-the-shelf components. Its tiny size (1.5 × 3.0 mm^2) makes system miniaturization possible, and the bio-sensing system suitable for high-density multi-electrode systems.

Printed electronics is an approach to enable cost-effective manufacturing with the use of inexpensive disposable paper substrate and low-waste print-on-demand inkjet printing technology [11]. The fabrication of printed electrodes and the performance will be presented in Section IV.

Composed of five metal traces printed on a flexible substrate, an inkjet-printed flexible Active Cable can be used to connect multiple bio-sensing chips in series. The Active Cable not only serves as the power supply but also provides the communication channel for system commands and data exchange. The concept and performance of Active Cable were presented in the previous paper [12]. A wireless module can also be included in the bio-sensing system to build a network and transmit sensed data.

III. Analog Front-End of Bio-Sensing System-on-Chip

The bio-signal SoC is mainly composed of three functional blocks, including an Analog Front-End (AFE), a back-end Successive Approximation Register Analog to Digital Converter (SAR ADC), and a digital core. The block diagram and photograph of the bio-signal SoC are shown in Fig.1 and Fig.2. More details about the SoC design and the performance of the ADC and the digital core can be found in the previous paper [13]. Here we focus on the AFE block.

The AFE block is an integral part of the SoC, because it should meet strict requirements of physiological signals measurement. The amplitudes of these signals range from tens of µV to several mV and the frequencies from DC to hundreds of Hz. In order to accommodate the weak signals and achieve the high-dynamic range, three-stage bio-signal front-end is used in this work (Fig.1) with a programmable gain and bandwidth. A set of switches is employed on the test board to control the gain and bandwidth of the AFE. Combining three stages, the total close-loop gain of the AFE can be configured from 175 V/V to 1660 V/V. The power consumption of the AFE block is 2.76 µW from a 1.2 V supply. For the *in-vivo* tests performed in Section IV, the gain is configured to 600 V/V, and the pass-band is set between 0.5 Hz and 260 Hz.

The input impedance of the circuit is designed to be higher than conventional system to minimize the loading effect. In this work, it is around 40 GΩ @ 100 Hz. This high input impedance reduces the influence of resistance induced by printed electrodes and their interconnections.

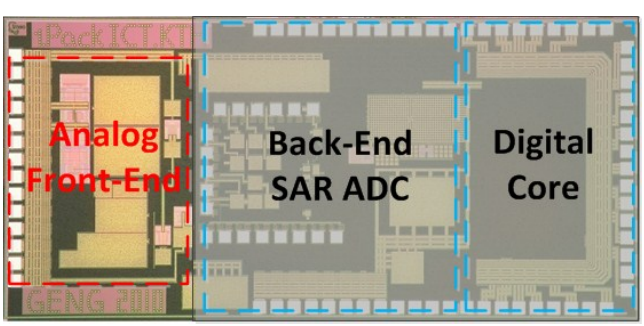

Fig. 2. Microphotograph of the bio-sensing SoC.

IV. Inkjet Printed Electrodes on paper substrate

Conventional Ag/AgCl wet electrodes with electrolyte gel are commonly used in ECG monitoring applications, but the signal quality degrades when the gel dries out. Here we propose the paper-based inkjet-printed electrodes.

A. Manufacture of Paper-Based Inkjet-Printed Electrodes

In this work, NPS-JL (nano-particle silver inkjetable low-temperature ink from Harima Chemicals) is directly printed on photo-paper by inkjet printer (DMP2800 from Dimatix) with 10 pl printhead. The drop size for photo-paper is around 28 um. Therefore, the inkjet processing resolution is set to be 1270 dpi (drop spacing of 20 um). This means enough overlapping between drops in order to have a smooth and solid conductive film. The ink is sintered at 120 ºC in an oven in air for one hour. The surface roughness of one-layer printed electrode on photo-paper is around 10 nm. To compare the performance, commercial electrodes (Tyco Arbo H124sg pre-gelled electrodes) are used. The printed electrodes are designed to be 15 mm diameter round, the same with the commercial ones. Interconnects are also printed on paper substrate to offer connection trace from electrodes to inputs of the chip. The printed pattern has stable conductivity of around 6 MS/m, about 10% of silver bulk conductivity (63 MS/m).

The printed interconnections bring in certain resistance compared with ideal metal wires. Suppose the width of printed interconnections remain the same, the resistance increases linearly along with the distance between two electrodes. Moreover, the variation of electrodes distance also leads to the change of bio-potential sensed by electrodes. Therefore, we did investigation on how the variation of printed electrodes distance affects the detected bio-signal.

We designed 6 samples, as shown in Fig.3. 5 samples (from Sample 1 to Sample 5) are symmetric structures, which mean the length of left side (L_L) interconnect equals to the right one (L_R). The length of symmetric samples varies from 6

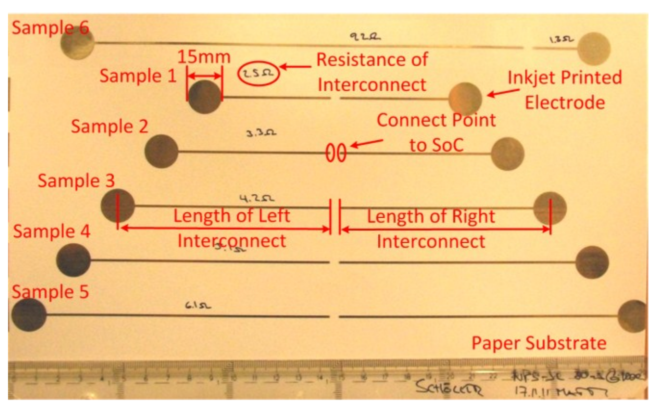

Fig.3 Inkjet-printed electrodes on photo-paper substrate.

cm to 14 cm with a step of 2 cm.

Since the analog circuit takes a fully differential structure to suppress the common mode environmental noise, any circuit mismatch will induce the degradation on common mode rejection ratio, thus contaminating the output signal. Besides the symmetric samples, we designed Sample 6 with an unsymmetrical structure to figure out the importance of symmetry, L_L is 3 cm and L_R is 21 cm. The total distance between two electrodes of Sample 6 (3 cm + 21 cm) equals to Sample 4 (12 cm + 12 cm).

B. *ECG* In-Vivo *Test with Printed Electrodes*

The ECG signal measurement setup and equivalent circuit are shown in Fig.4. Two electrodes are connected to the differential inputs of AFE block. The gain and bandwidth of AFE are set to 600 V/V and 0.5 Hz ~ 260 Hz. The output of AFE is measured by the oscilloscope (TDS 3054). The contact impedances of left-side and right-side electrodes are represented by Z_a and Z_b in Fig.4. The resistance of left and right interconnects are respectively presented by Z_L and Z_R. Z_{in} is the equivalent input impedance of the circuit. ECG signals are successfully captured by attaching the printed electrodes to human subject's chest. During monitoring, the electrodes are placed towards the chest. A thin layer of nonconductive adhesive is applied at the edge of paper substrate to ensure stable mechanical contact between the electrodes and the skin.

C. *Performance of Printed Electrodes with Symmetric and Unsymmetric Interconnects*

The ECG signals captured by Sample 4 (symmetric structure) and Sample 6 (unsymmetric structure) are compared with pre-gelled Tyco Arbo H124sg electrodes. In order to compare the noise, we apply Fast Fourier Transform (FFT) to the circle-marked noise parts. The results are shown in Fig.5. Since the measurements are performed in a typical electrical engineering laboratory, the ECG signal cannot be immune from the 50 Hz power-line interference. The FFT result indicates that 50 Hz power-line interference is a dominant noise source.

In Fig.5, the average signal amplitude of printed electrodes is bigger than commercial ones. For the commercial electrodes, a thin conductive gel layer is applied on top of the

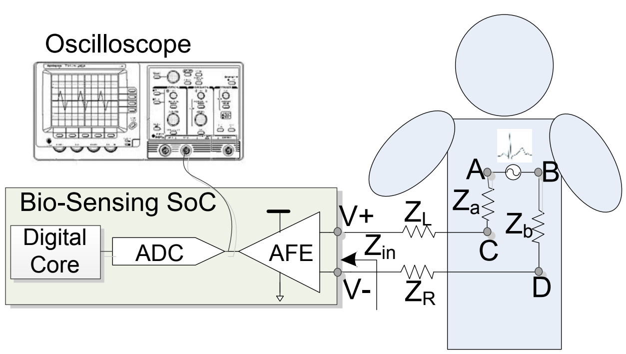

Fig.4 ECG signal measurement setup and the equivalent circuit.

metal plate to ensure stable contact with the skin. As a result, the contact impedance of the pre-gelled electrode (around 350 kΩ [14]) is much higher than our inkjet printed electrodes, the metal layers of which directly contact with the skin. Suppose the signal source (ECG signal) and Z_{in} keep constant, a higher contact impedance leads to a smaller input signal at AFE's inputs. Since the gain and bandwidth are unchanged, the final magnitude of ECG signal observed from oscilloscope linearly

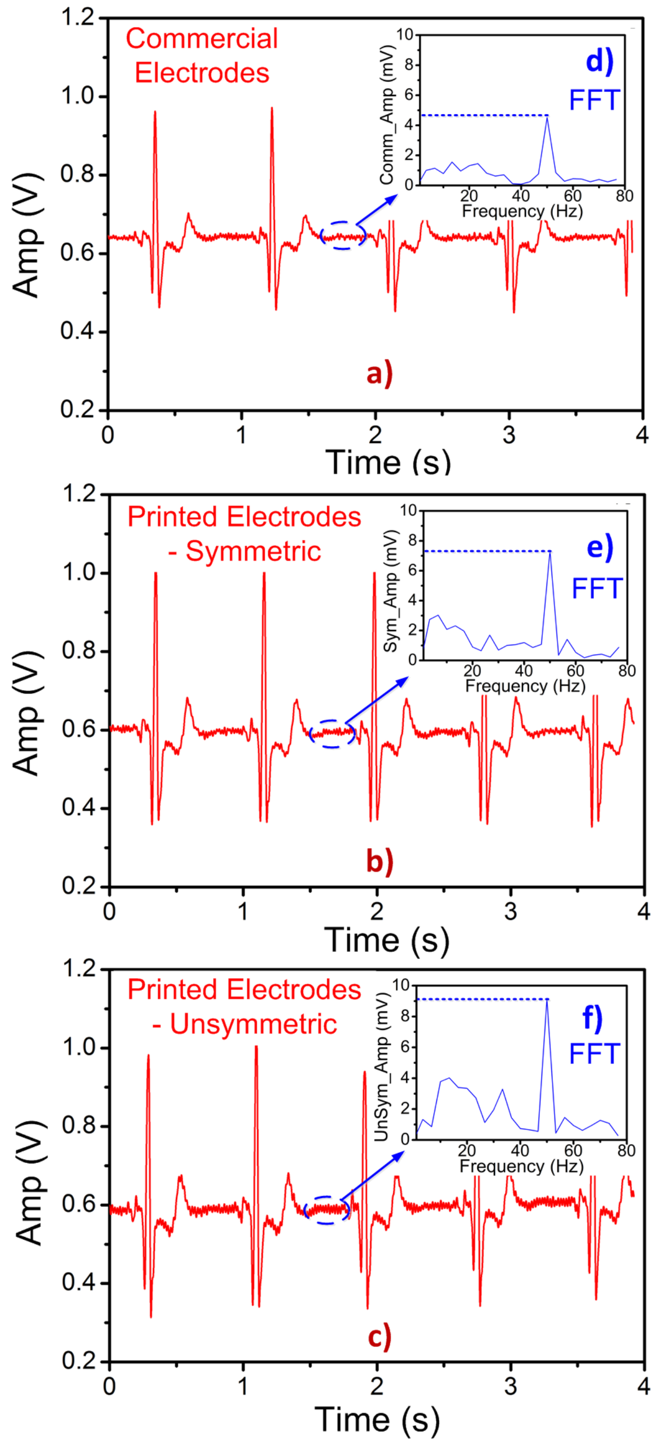

Fig.5 Captured ECG signal with a) commercial electrodes, b) printed electrodes with symmetric interconnects and c) unsymmetric interconnects, and the respective FFT analysis of the noise d) e) and f).

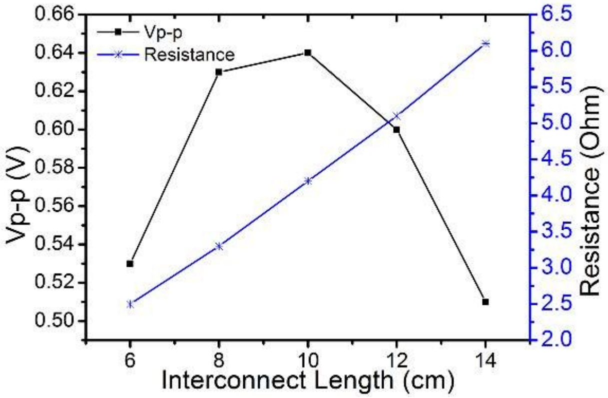

Fig.6 Signal strength and resistance vs electrode distance.

increases with the strength of AFE input signal. Therefore from the perspective of magnitude, the ECG signal from inkjet printed electrodes is even better. The resistance variation caused by asymmetry is only several ohms. Compared with the high input impedance of the circuit, it is insignificant and ignorable. Therefore, signal strength of the unsymmetric and symmetric structure shows little difference.

However, the direct contact of inkjet printed electrodes is not as stable as the pre-gelled ones, which leads to more electrode contact noise. That is the reason why the ECG signal noise from printed electrodes (0.74 mV @ 50 Hz) is bigger than the pre-gelled ones (0.45 mV @ 50 Hz). The unsymmetric interconnects contribute even higher noise value (0.92 mV @ 50 Hz). This is because we employ fully differential circuit architecture in the front end amplifier to reject environmental noise, while the unsymmetric structure introduces unmatched noise. Anyhow, the variation of noise is below 1 mV. Compared with the amplitude of measured ECG signal (around 600 mV), the noise variation is slight.

The experiment results indicate that the design of SoC enables the ECG signal to be less dependent on the structure of interconnects, and that the overall performance of inkjet printed electrodes is comparable with commercial ones. In other words, inkjet printed electrodes are potential substitutes of commercial electrodes.

D. *The Influence of Electrode Distance*

Fig.6 shows DC resistance and the magnitude of ECG signal from Sample 1 to Sample 5. The DC resistance of interconnects is measured by a multimeter. The figure indicates DC resistance linearly increases with the interconnect length. During the ECG measurements, the right electrode of the printed electrode pairs is placed on a fixed point of the chest, while the position of the left electrode alters. The magnitude does not monotonically increase along with the distance. The interconnect length of 10 cm makes the highest signal strength. At a distance of 6 cm, the signal is still strong enough for ECG monitoring. The result suggests that we can choose suitable interconnect length according to the chest size in the range above.

V. Conclusion

A hybrid wearable bio-sensing system is presented in this paper. The traditional system-on-chip and printed electronics are combined in the hybrid system and offer their advantages. The high-performance bio-sensing SoC fulfills the functional requirements of bio-monitoring system, including signal sensing, digitizing and data processing. The input impedance of SoC is designed to be high enough to make the ECG signal less dependent on the structure of interconnects. The use of a tiny-size SoC ensures a miniature bio-sensing system. ECG *in-vivo* test is applied to evaluate the performance of paper-based inkjet-printed electrodes. The preliminary measurement result indicates that printed electrodes have comparable performance with the commercial ones, with slightly increased noise. The little difference of ECG signal between symmetric and unsymmetric structure indicates great freedom while designing printed electrodes pattern. The SoC and printed electrodes based hybrid bio-sensing system offers a promising solution for the next generation wearable healthcare technology.

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