31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

A 1.0 V 78 µW Reconfigurable ASIC Embedded in an Intelligent Electrode for Continuous Remote ECG Applications

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Abstract—In this paper, a reconfigurable, low-power Application Specific Integrated Circuit (ASIC) that extracts and transmits electrocardiograph (ECG) signals is presented. An Intelligent Electrode is introduced which consists of the proposed ASIC and a micro spike array, permitting onsite ECG signal acquisition, processing and transmission. Fabricated in a standard 0.18 µm CMOS process, the ASIC consumes 78 µW with 1.0 V core voltage at 6 MHz operating frequency and only occupies 2.25 mm^2. The tiny silicon size makes it possible and suitable to embed the proposed ASIC into an Intelligent Electrode, and the low power consumption makes it feasible for long term continuous ECG monitoring.

I. Introduction

Healthcare in many countries around the world encounters several major challenges in the near future. The cost of healthcare is growing rapidly world wide due to the increasingly aging population and the ascending number of chronic diseases for the elderly as well as the young. According to the statistics from Statistical Office of the European Communities (Eurostat), the cardiovascular diseases (CVD) including diseases of the heart and circulatory system accounts for 41% of all deaths, which comprise the biggest cause of death in 25 EU countries [1]. In response to these trends, it is necessary to utilize new technologies to make healthcare services more efficient, more personalized and significantly cheaper.

ECG monitoring and analysis systems have been explored in many companies and research organizations [2], [3]. However, several unsolved problems still exist. The major disadvantages of existing ECG solutions include the following three aspects: 1) a large number of connecting cables make it uncomfortable in patients' daily life; 2) high-quality ECG data are difficult to obtain; 3) high power consumption becomes an obstacle for long-term monitoring.

To overcome the challenges mentioned above, this paper introduces an Intelligent Electrode with a low power ASIC embedded inside [4], [5]. The Intelligent Electrode is comprised of an amplifier, an analog filter, an A/D convertor and the proposed ASIC. A prototype of the Intelligent Electrode is built to evaluate its performance. Fig. 1 plots the flow diagram of ECG signals acquisition and transmission process with the proposed Intelligent Electrodes.

Manuscript received April 23, 2009.

This work was financially supported by Vinnova (The Swedish Governmental Agency for Innovation Systems) through the Vinn Excellence centers program.

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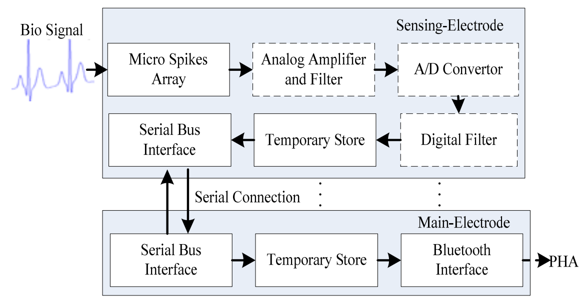

Fig. 1. ECG signals acquisition, processing and transmission in an Intelligent Electrode.

The rest of this paper is organized as follows. Section II describes the function of the Intelligent Electrode and explains the methods of obtaining high quality ECG data using a micro spike array and an Active Cable. Section III illustrates the chip VLSI realization in a standard CMOS technology and measurement results from an Intelligent Electrode prototype. Conclusion is made in Section IV.

II. A Wearable ECG Monitoring System Based on Intelligent Electrodes and an Active Cable

Traditional healthcare and well-being services are usually provided within hospitals or medical centers. As a result, measurements of vital signs and diagnosis are carried out in controlled environments. Technical progress extends healthcare into the home environment, since this service is more convenient and less expensive [6]. A monitoring system for early detection of changes in patients' health is presented in this paper, as shown in Fig. 2(a). The system measures a patient's ECG signals automatically by applying multiple Intelligent Electrodes and an Active Cable.

A. Micro Spike Array

The most commonly used ECG electrodes in the clinical field are pre-gelled and solid gel silver/silver chloride (Ag/AgCl) adhesive electrodes. These electrodes are simple, lightweight, reliable and cost effective. However, adhesive electrodes have drawbacks when used in long term monitoring applications. 1) Mechanical abrasion (skin pretreatment) together with the adhesive gel cause damages to the skin, such as irritations or allergic reactions. 2) The

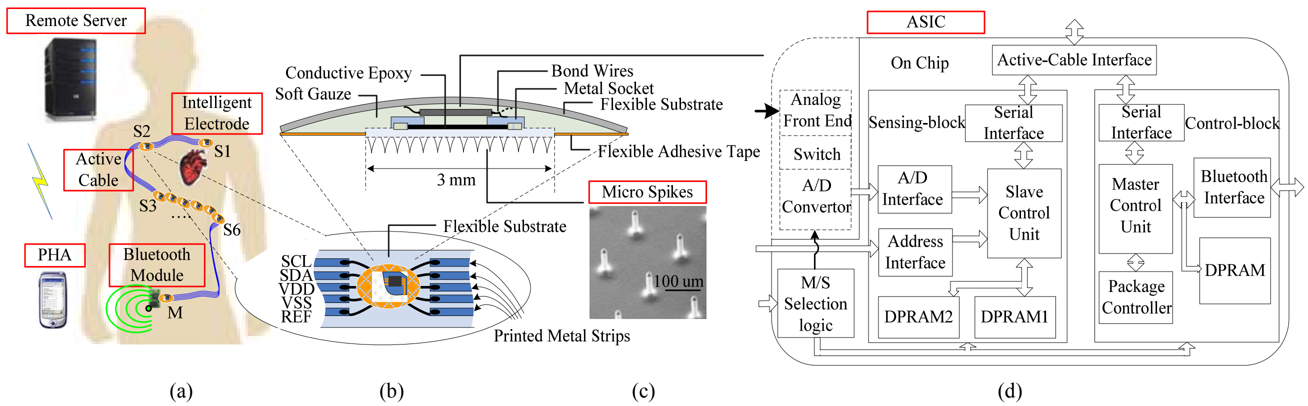

Fig. 2. (a) Proposed wearable ECG monitoring system;. (b) Interconnection between an Intelligent Electrode and an Active Cable; (c) Micro spikes array; (d) Block diagram of the ASIC

contact impedance between the electrode and the skin becomes unstable when gelled electrodes dry out. Electrode motion results in contact interference which contributes significantly to the signal noise. To minimize the electrode contact noise which is a transient interference caused by loss of contact between the electrode and the patient skin, micro spike technique is adopted in this design, as shown in Fig. 2(c) [7]. Compared with conventional ECG monitoring approaches, integrating a micro spike array beneath the gauze plaster allows us to obtain high quality ECG signals. Without any skin pretreatment, improved electrical contact can be achieved by penetrating the dead skin cells with these micro spikes. The spikes are fabricated with Micro Electro Mechanical Systems (MEMS) technology with a proper length: 100 µm long for each spike. The expected operational life time for a micro spikes array is not less than 3 days after it is placed on a patient's skin. The electric path between a micro spikes array and an ASIC chip is shown in Fig. 2(b), where the bio-potential collected by the spikes is transmitted to the ASIC input port via a metal socket and a bonding wire.

B. Intelligent Electrode

As shown in Fig. 2(b), the proposed Intelligent Electrode consists of a 10 mm × 10 mm gauze plaster, a 3 mm × 3 mm array of micro spikes attached beneath, and a 1.5 mm × 1.5 mm ASIC chip embedded in the middle. The gauze plaster is used as a soft substrate, while the micro spike array is used to penetrate the out layer of human skin for better signal quality. Within each Intelligent Electrode, an amplifier, an analog filter, an A/D convertor and digital communication interface are integrated. Instead of having the measurement performed in a stationary or portable medical device, the ECG signal amplification, filtering, digitization and transmission tasks are performed directly onsite.

The analog signal from the patient's skin is firstly amplified and filtered in the analog front-end module, then digitized by a 14-bit Delta-Sigma A/D convertor at a certain sample rate, and then stored locally in an on-chip dual port RAM (DPRAM) temporarily, finally transmitted wirelessly to a personal health assistant (PHA) via Bluetooth link, as shown in Fig. 2(d). A 1.8 V LR44/A76 Alkaline button cell battery is used as the power supply for both Bluetooth module and Intelligent Electrodes.

Due to the reconfigurable property of the ASIC, each Intelligent Electrode can be configured either as a Main-Electrode or a Sensing-Electrode. From the function point of view, the Main-Electrode: 1) provides reference signal needed for A/D conversion on Sensing-Electrodes, 2) controls all Sensing-Electrodes in the system, 3) collects ECG data from each Sensing-Electrode, 4) provides interface to a Bluetooth module. While the Sensing-Electrode carries out the following tasks: 1) ECG signal conditioning (amplification and filtering), 2) ECG signal digitization with an A/D convertor. If a Main-Electrode is disabled, another Intelligent Electrode can be configured as a Main-Electrode to take over its duties.

C. Active Cable

Biological signal amplification circuits in ECG monitoring devices measure very small electrical signals emitted by the body, often as small as several micro-volts. Unfortunately, in currently available ECG monitoring devices, the cables used to transmit these small biological signals to a measuring equipment act as antennas that are prone to be perturbed by electrical interference, especially 50 Hz or 60 Hz noise from electrical outlets. These interference voltages are often larger than the biological signals themselves, making the biological signals hard to be distinguished.

Moreover, a large number of cables are required to connect electrodes with a central device in most ECG monitoring applications. For example, 3 cables are necessary for a 3-lead ECG monitoring, up to 9 or 10 cables for a 12-lead ECG monitoring. These cables are inconvenient for patients which restrict patients' mobility. The increasing number of cables does not only bring considerable electrical noise into signal acquisition circuit, but also decrease the convenience and comfort for patients in their daily life.

To overcome the obstacles mentioned above, the technique challenge here is to minimize the number of connecting cables, while get 12-lead ECG signals with even better quality. The Active Cable is proposed to achieve this goal. It is composed of five flexible metal strips with high conductivity printed on flexible PET or PVC substrates. Instead of multiple cables, a single Active Cable is used to connect all the Intelligent Electrodes together, over which ECG data and control commands are transferred.

A cross-section view of the Active Cable is illustrated in Fig. 2(b). A microchip is fitted into a soft gauze holder and connected with the printed metal strips by bond wires. The Active Cable is designed on a breathable and adhesive substrate thus can be easily attached around a patient's torso.

The Active Cable is composed of five thin metal strips: REF, SCK, SDA, VDD and VSS respectively. REF is taken as an analog reference signal used for A/D conversions. All ECG data are obtained by digitizing the voltage difference between the electric potential of a local measurement point and the REF signal. In this design, the Main-Electrode provides its local bio-potential as REF. A two-wire bus, SCK and SDA is used to transmit ECG data and broadcast commands. The metal strip SCK carries the serial unidirectional clock and SDA carries serial data, which is a bidirectional signal. The last two wires in the Active Cable are VDD and VSS which are the digital power and digital ground respectively. In order to minimize the electrical cross-talk induced by neighboring wires, especially the noise generated by serial bus, REF is properly shielded by VSS and placed far away from SCK and SDA.

The overall goals of the Active Cable are to: 1) replace conventional multiple connecting cables with one cable only, 2) achieve high quality ECG data by minimizing the electrical interference coupled by connecting cables, 3) improve users' comfort and enable long-term monitoring.

III. Hardware Implementation and Measurement Results

A. Hardware Implementation

The proposed ASIC was implemented into a silicon chip by using 1-poly 6-metal 0.18 µm Mixed-Mode CMOS technology occupying a total area of 1500 µm × 1500 µm. The microphotograph of the fabricated ASIC is shown in Fig. 3(a). It can be seen that three pieces of DPRAM occupy a relatively large percentage of the total chip area.

To facilitate the measurements, a CQFP-64 package was adopted to encapsulate the ASIC in. A 6 cm × 5 cm circuit board was designed to verify the ASIC function blocks and measure the power consumption as well as other electrical parameters. During the circuit functional verification, several ECG data patterns were generated using a data generator and served as inputs to a Sensing-Electrode. Broadcast commands and ECG data between a Main-Electrode and a Sensing-Electrode are transferred via a serial interface, as shown in Fig. 3(b).

B. Measurement Results

Low power consumption is one of the most important features of battery operated long-term ECG monitoring systems. In this section, experiments are made to show the ASIC power consumption variation caused by the change of chip power supply and operating frequency. Although the standard operating voltage for this 0.18 µm CMOS process is 1.8 V, a comprehensive test was carried on to investigate how to minimize ASIC power consumption by tuning the core voltage and the operating frequency. We find that both the Main-Electrode and Sensing Electrode operate well when the core voltage is tuned down from 1.8 V to 0.9 V with a step of 0.1 V at the operating frequency of 24 MHz. When the supply voltage is lower than 0.9 V, the ASIC fails to work. As we can see in Fig. 4, the power consumption decreases dramatically when the core voltage is tuned down from 1.8 V to 0.9 V: the power consumption drops from 1067 µW to 249 µW for the Main-Electrode, while 1035 µW to 240 µW for the

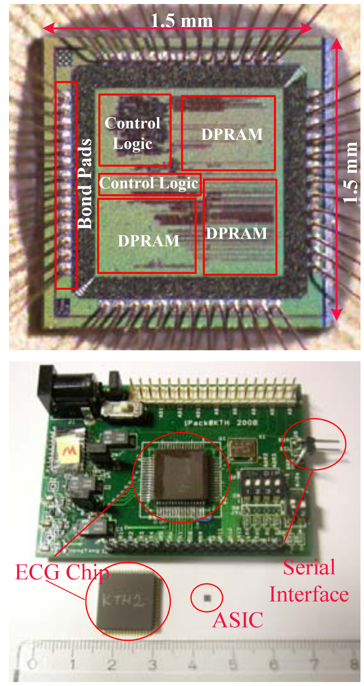

Fig. 3. (a) ASIC fabricated in 0.18 µm CMOS; (b) Measurement board, packaged ECG chip and the silicon die of the proposed ASIC.

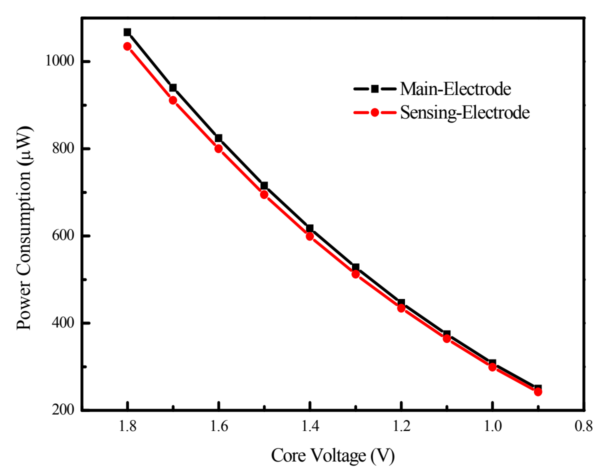

Fig. 4. Power consumption for a Main-Electrode and a Sensing-Electrode with the core power supply ranging from 1.8 V to 0.9 V at 24 MHz ASIC frequency.

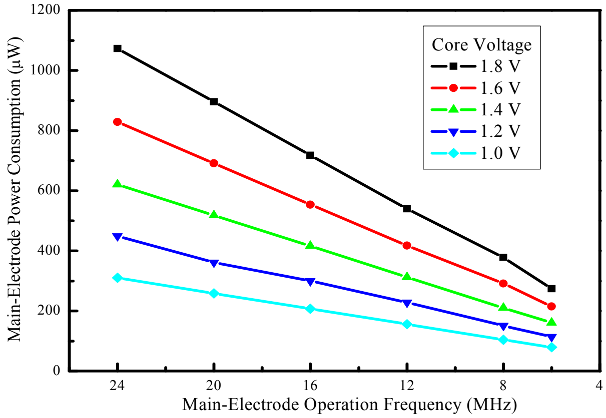

Fig. 5. Power consumption for a Main-Electrode with core voltage ranging from 1.8 V to 1.0 V at ASIC frequency ranging from 24 MHz to 6 MHz.

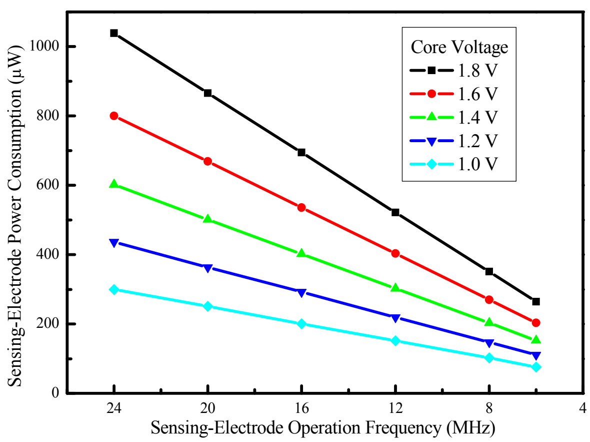

Fig. 6. Power consumption for a Sensing-Electrode with core voltage ranging from 1.8 V to 1.0 V at ASIC frequency ranging from 24 MHz to 6 MHz.

Sensing-Electrode. The measurement result shows that the power consumption is proportional to the square of the operating voltage. In order to make the following measurements stable, we set the ASIC core voltage not lower than 1.0 V. The cell leakage power is 2.3 µW for both Main-Electrode and Sensing-Electrode with a 1.8 V core voltage.

Another major issue affecting the ASIC power consumption is the operating frequency. As shown in Fig. 5 and Fig. 6, when the operating frequency is tuned down from 24 MHz to 6 MHz, the power consumptions for both Main-Electrode and Sensing-Electrode decrease linearly. The minimal power consumption is achieved when the ASIC is operating at 6 MHz with 1.0 V core voltage supply: 78 µW for the Main-Electrode and 74 µW for the Sensing-Electrode. Moreover, the AISC is designed for an event-driven scenario, where the ECG signal sample rate is scalable. Whenever any abnormality appears for a patient's heart rate, the ASIC operating frequency will be switched to 24 MHz automatically with an ECG sample rate of 1000 samples/s for an intensive monitoring. When under normal circumstances, the ASIC works at power saving mode with 6 MHz operating frequency and a sample rate of 250 samples/s for a longer battery life. The main characteristics of the Main-Electrode and the Sensing-Electrode are summarized in Table I.

TABLE I
PERFORMANCE SUMMARY

Process Technology	1P 6M 0.18 µm CMOS
Supply Voltage	0.9 V – 1.8 V
ASIC Frequency	6 MHz – 24 MHz
Sample Rate	250 Hz @ 6 MHz ASIC Frequency 1000 Hz @ 24 MHz ASIC Frequency
Sample Resolution	14 bits
Serial Bus Transmission Rate	1 Mbps @ 6 MHz ASIC Frequency 4 Mbps @ 24 MHz ASIC Frequency
Main-Electrode Power Consumption	78 µW @ 6 MHz ASIC Frequency and 1.0 V Core Voltage 273 µW @ 24 MHz ASIC Frequency and 1.0 V Core Voltage
Sensing-Electrode Power Consumption	76 µW @ 6 MHz ASIC Frequency and 1.0 V Core Voltage 265 µW @ 24 MHz ASIC Frequency and 1.0 V Core Voltage
Leakage Power	2.3 µW @ 1.8 V Core Voltage
Silicon Die Size	1500 µm x 1500 µm
Package	CQFP-64
Number of Sensing-Electrodes	Support up to 12 Sensing-Electrodes

IV. CONCLUSION

A reconfigurable ASIC which is integrated in an Intelligent Electrode has been presented. Tailored for a long term continuous ECG monitoring, the ASIC is fabricated in a standard 0.18 µm CMOS technology, consumes 78 µW with 1.0 V core voltage at 6 MHz operating frequency and occupies only 2.25 mm^2. The ASIC functionality verification and power consumption measurement have been successfully carried out on a prototype board.

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