Proceedings of the 5th International Workshop on Wearable and Implantable Body Sensor Networks, in conjunction with
The 5th International Summer School and Symposium on Medical Devices and Biosensors
The Chinese University of Hong Kong, HKSAR, China. Jun 1-3, 2008

A Wearable BSN-based ECG-recording System Using Micromachined Electrode for Continuous Arrhythmia Monitoring

D. G. Guo, Francis E. H. Tay*, L. M. Yu, L. Xu, M. N. Nyan, F. W. Chong, K. L. Yap, B. Xu

Abstract— **A wearable BSN-based ECG-recording system is proposed for long-term and continuous arrhythmia monitoring. A novel micromachined Pt electrode is specifically designed, fabricated and integrated into a wearable chest band. A miniaturized PCB for ECG analog front-end is fabricated, and can be plugged on the BSN node to wirelessly transmit the signal to a hand-held device. Wavelet denoising is implemented on the hand-held device to further reduce the noise induced by electrode contact. Once a beat is detected, it is characterized by a number of features such as width, amplitude and rhythm pattern, and different types of arrhythmias can then be real-time classified. Once sentinel events such as arrhythmia is detected, the abnormal ECG signal can be sent wirelessly by hand-held device through GPRS to doctors or caregivers for prompt analysis and further treatment.**

I. Introduction

Healthcare is facing major challenges in the near future as costs are rapidly increasing world wide due to aging population and widespread chronic diseases. Singapore is no stranger to the challenges posed by an aging citizenry: it has the fastest growing elderly population in the world. Singapore, as being unique among developed countries in achieving high quality health care, is actively advancing the application of biomedical research in developing low cost and cost effective medical systems in healthcare service. 15 years down the line, the population of elderly above 65 years old is estimated to double from 10% to 20% and the country's ratio of workers-to-elderly will shrink from 11:1 today to 4:1 by 2025 [1]. This situation posts a problem of hospital beds not being able to meet the number of patients to be admitted. Furthermore, transient abnormalities cannot always be captured in the hospital. Many cardiac diseases are associated with episodic rather than continuous abnormalities whose timing cannot be predicted, and as a result, important and even life threatening disorders will be undetected and may never be recorded objectively. Therefore, remote and continuous monitoring for reliable detection of these episodes, such as myocardial ischemia or ventricular arrhythmia, becomes essentially useful especially for elderly patients with end-stage heart disease.

Currently, traditional ECG (Electrocardiogram) Holter monitoring is still the most widely used technique which can record up to 24 hours of ECG signals, and the recorded data is subsequently retrieved and analyzed by a clinician. Based on this, more research have been conducted to develop the advanced ECG monitoring systems, which can real-time detect the arrhythmia and generate the warning signal once event is captured[2], or integrate with wireless transmission and GPS (Global Positioning System) sensor. However, an ideal long-term and continuous monitoring system should measure vital signs with almost no impact on quality of life. For these conventional systems, classical medical wet electrodes are fixed to the skin by an adhesive, which can cause irritation or even a rash due to an allergic reaction as a result of gels drying. On the other hand, conventional dry electrodes can directly measure the biopotential using high impedance-converting amplifier incorporated in the electrode, but face the problem of bulky size and high cost which are induced by the additional electronics and the required power sources.

In this paper, novel micromachined Pt electrodes are specifically designed and fabricated to meet the challenges mentioned above. The novel electrodes are integrated in a wearable chest band and connected to the BSN node [3-4], where the collected ECG signal will be transmitted to a PDA phone. The developed ECG-recording system can continuously characterize the ECG signal by a number of features such as width, amplitude and rhythm pattern. Once sentinel events such as arrhythmia is detected, the abnormal ECG signal can be sent wirelessly by hand-held device through GPRS to doctors or caregivers for prompt analysis and further treatment.

II. Micromachined Electrode

A. Concept

Since the electrodes need to be placed on the surface of the skin during the measurement, it is essential to understand the skin anatomy in order to understand the basics of biopotential measurements [5]. The outer skin layer Stratum Corneum (SC)

Manuscript received Jan 25, 2008. This work was supported by the Embedded and Hybrid System (EHS) programme supported by the Agency for Science, Technology and Research (A*STAR) under the grant 052-118-0051.

Francis E. H. Tay is an associate professor of Mechanical Engineering Department, National University of Singapore (National University of Singapore Department of Mechanical Engineering P.O.Box 119260, Singapore, mpetayeh@nus.edu.sg, 65-65167130). He is also the medical device group leader with the Institute of Bioengineering and Nanotechnology (IBN). Dr. Tay was also the founding director of the Microsystems Technology Initiative (MSTI), and had established the Microsystems Technology Specialization. He had also served as the technical advisor, in the Micro and Nano Systems Laboratory, Institute of Materials Research Engineering (IMRE).

D. G. Guo, L. M. Yu, L. Xu, M. N. Nyan, F. W. Chong, K. L. Yap, B. Xu are with the Mechanical Engineering Department, National University of Singapore

consists of dead cells and acts as a fluid barrier which has electrical isolation characteristics. The Stratum Germinativum (SG) is the area where the cells divide, grow and are displaced outward to the SC. Since the SG is composed of living cells which predominantly consist of liquid, this layer of the skin is an electrically conducting tissue comparable to an electrolyte. The dermis, which is below the SG, contains vascular and nervous components as well as sweat glands and hair follicles and is also electrically conducting. Thus it can be seen that a more stable electrode will result if the effect of the SC (i.e., electric impedance that behaves as a parallel RC circuit) can be reduced.

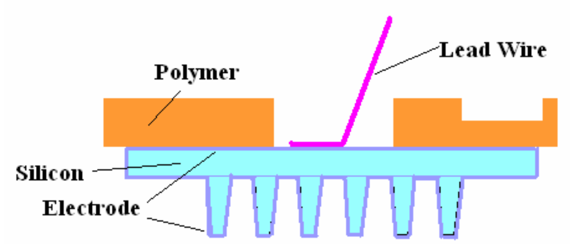


Fig.1 Schematic view of novel micromachined electrode doped with Pt

The schematic view of the micomachined electrode doped with Pt is shown in Figure 1. The extruded microneedle can pierce though the outer SC layer and directly contact with the SG layer, which eliminates the need for abrasion of the SC layer and substantially lowers down the high impedance caused by SC layer as shown in Fig.2, where E_{hc} is the half-cell potential of the electrode, R_d and C_d make up the impedance associated with the microneedle-SG interface, and R_u is the effective resistance associated with SG and underlying tissue. For subsequent signal acquisition and processing, the micromachined electrode needs to be connected to analog electronics by a lead wire. Since the wire diameter is substantially larger than the length of the microneedles, it must be attached to the back of the electrode to avoid any influence on the proper penetration of the needles into the skin. Electrical interconnection between the front and the back of the electrode chip is established by depositing Pt layer on the both sides of the silicon substrate. A polymer disk is then bonded to the silicon substrate to provide support. Compared with the reported micromachined electrode doped with Ag/AgCl [6], our electrode does not involve electrochemical cell process, which makes it low-cost and more suitable for batch production.

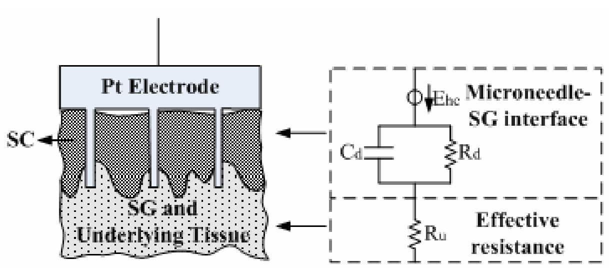


Fig.2 Electrical equivalent circuit of micromachined electrode

B. Fabrication Process

The fabrication processes of the micromachined electrode are shown in Fig.3. Firstly, a 2 μm-thick SiO_2-PECVD layer is deposited on a silicon wafer with <100> crystallographic orientation, p type, and thickness of 500 µm using an STS Multiplex ProCVD tool (Temperature: 300 ^OC, SiH_4 and N_2O gases, Pressure: 900 *mTorr*, Power: 500 *W* at 13.56 *MHz* RF mode). On the top of this layer, a thin film photoresist mask (AZ7220 from Clariant) was deposited using a classical photolithographic process. The photoresist mask was transferred to the silicon oxide layer using a plasma etching process in an ICP deep RIE Adixen 101-DE where CHF_3/He are used as the process gases. After that, the photoresist layer was removed in a photoresist stripper. A cleaning process in piranha at 120 ^OC for 20 minutes was performed to remove the residual photoresist. Subsequently, the extruded microneedle array with a diameter of 80µm was performed using an anisotropic deep RIE Bosch process in an Adixen 101 ICP- deep RIE where SF_6/C_4F_8 are used as the process gases. The depth of the microneedles is around 150 µm. Finally, the silicon wafer is cut into small pieces using dicing saw and a Pt layer is deposited on the both sides of the silicon die to provide the electrical connection to the outside wire using E-beam evaporator.

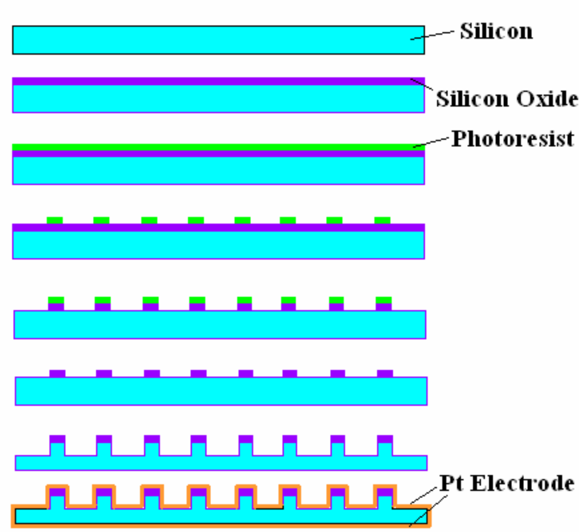


Fig.3 Fabrication process of novel micromachined electrode doped with Pt

C. Fabrication result

The SEM photo of fabricated Pt micromachined electrode with microneedles is shown in Fig.4

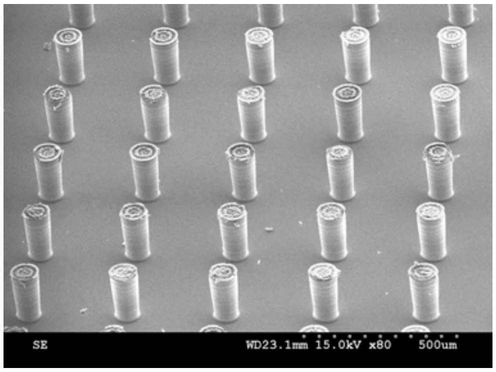


Fig.4 SEM photo of fabricated Pt micromachined electrode

III. WEARABLE ECG-RECORDING SYSTEM

A. Concept

An ideal ECG-recording system for long-term and continuous monitoring should measure the ECG signal with almost no impact on quality of life. To realize this idea, the fabricated electrode will be integrated into a chest band for easy worn. As shown in Fig.5, a miniaturized PCB board includes analog front-end for ECG signal acquisition is designed and fabricated, which can be attached on a BSN node and wirelessly transmitted the measured ECG signal to a hand-held device such as PDA phone. BSN (Body Sensor Network) was coined by Prof Guang-Zhong Yang of Imperial College London in 2002. It is a hardware platform implementing TinyOS, which is an open-source operating system designed for wireless embedded sensor networks. The compact size and low power consumption make BSN mote suitable for wearable and wireless applications. Currently, the fabricated PCB board includes its own MSP430FG439 microcontroller unit (MCU) for signal acquisition and preliminary signal processing, and the output data are sent to a BSN node via UART port and then relayed to the hand-held device, where BSN mote is used as a Zigbee wireless transceiver.

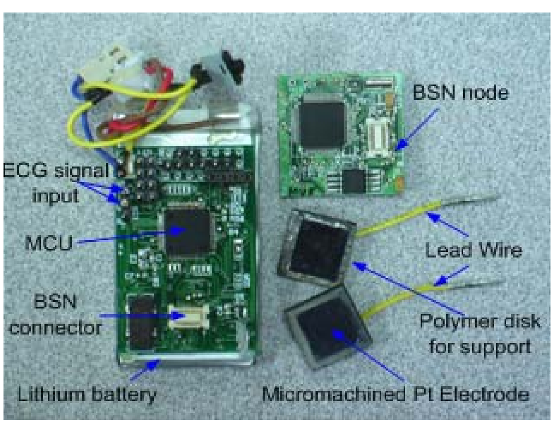
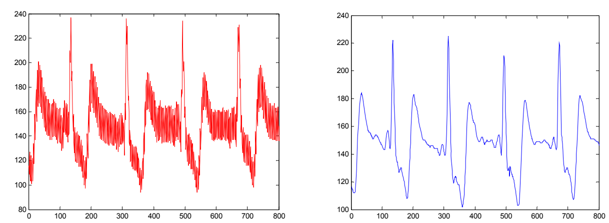


Fig.5 Schematic view of prototype hardware

B. Signal processing and arrhythmia detection

The ADC12 in MCU of PCB samples the ECG signal with a sampling frequency of 200 Hz and two linear phase symmetrical FIR filters are implemented in MCU, where low-pass filter is used to remove high power line interference and high-pass filter is used to reduce part of the noise induced by electrode contact, muscle contraction and base line drift. Using symmetrical FIR filters can reduce the demand on math multiplication operations to one half because of the symmetrical nature of the filter coefficients. However, compared with conventional wet electrode, the novel micromachined Pt electrode display more signal noise which is normally induced by poor electrode contact. Therefore, once preliminarily processed ECG signal is wirelessly transmitted to a hand-held device, the wavelet denoising using mother wavelet of DB8 will be implemented to further reduce the noise. The noisy signal is firstly decomposed into three levels and then soft-thresholding denoising [7] is performed in each level of detail coefficients. Finally, the denoised signal is reconstructed where most of the white noise in original signal has been successfully removed as shown in Fig.6.



(a) (b)

Fig.6 (a) Original noisy ECG signal and (b) Denoised ECG signal using wavelet soft-thresholding denoising

Some tactics based on previous work [8] are applied in the QRS peak detection, where dual-threshold technique is used in searching-back process to find missed beats and thereby reduce false negatives. Two separate threshold levels in each of the two sets of thresholds are used where one level is half of the other. Since thresholds are based upon the most-recent signal and noise peaks that are detected in the ongoing processed signals, they continuously adapt to the signal characteristics. Once a beat is detected, it is characterized by a number of features such as width, amplitude and R-to-R interval and heart beat rate can be easily calculated by R-R interval. Also, different types of ailments or arrhythmias can be classified based on one lead ECG signal [9, 10].

1) Heart beat rate (HR):

Tachycardia: HR > 90 bpm (beats per minute)

Bradycardia: HR < 60 bpm

2) QRS width:

0.1~ 0.12 second indicates Wolff-Parkinson-White syndrome (WPW) or Non-specific intraventricular conduction delay (IVCD) or Incomplete right or left bundle branch block (RBBB or LBBB)

> 0.12 sec indicates Complete LBBB or RBBB or Ventricular tachycardia

3) Q Wave

If Q wave's width > 0.04 sec or/and Q wave's height > 25% of R wave's height indicates Myocardial Infarction (MI)

Once sentinel events, such as the arrhythmia types mentioned above, are detected, the abnormal ECG signal can be sent wirelessly by hand-held device through GPRS to doctors or caregivers for prompt analysis and further treatment.

IV. CONCLUSION

In conclusion, the proposed BSN-based ECG-recording system can be easily worn for remote, long-term and continuous arrhythmia detection, which has the potential to benefit not only the elderly but also the cardiac patients who has episodic abnormalities. We presented our preliminary results what we achieve so far and we are still working on designing a delicate chest band for more comfort and improving the overall system performance by detecting more types of ailment through the characterization of peak rhythm pattern and QT interval.

REFERENCES

[1] http://www.pacificbridgemedical.com/publications/html/AsiaJan1999.htm.

[2] P. Standing, M. Dent, A. Craig, and B. Glenville, "Changes in referral patterns to cardiac out-patient clinics with ambulatory ECG monitoring in general practice", *The British Journal of Cardiology*, June 2001, Vol. 8 , No.6, pp.396-398

[3] B. Lo, S. Thiemjarus, R. King, G. Yang, "Body Sensor Network – A Wireless Sensor Platform for Pervasive Healthcare Monitoring", *The 3rd International Conference on Pervasive Computing*, 2005

[4] B. Lo, G. Z. Yang, "Key technical challenges and current implementations of body sensor networks", *The 2nd International Workshop on Body Sensor Networks (BSN)*, 2005

[5] J .G. Webster, *Medical Instrumentation – Application and Design*, Houghton Mifflin Company, Boston, Toronto, 2nd edition, ch. 5

[6] P. Griss, P. Enoksson, H. K. Tolvanen-Laakso, P. Meriläinen, S. Ollmar, and G. Stemme, "Micromachined Electrodes for Biopotential Measurements", *Journal of Microelectromechanical Systems*, Vol. 10, No. 1, pp. 10-16, March 2001.

[7] D. L. Donoho, "De-Noising by Soft-Thresholding", *IEEE Transactions on Information Theory*, Vol. 41, No. 3, May, pp. 613-627, 1995

[8] P. S. Hamilton and W. J. Tompkins, "Quantitative investigation of QRS detection rules using the MITBIH arrhythmia database," *IEEE Trans Biomed. Eng.*, vol. BME-33, pp. 1157-1187, 1986.

[9] R. J. Huszan, *Basic dysrhythmias : interpretation & management (3rd ed)*, St.Louis : Mosby, 2002

[10] J. Huff, *ECG workout : exercises in arrhythmia interpretation (5th ed)*, Philadelphia: Lippincott Williams & Wilkins, 2006