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**Toward Wireless Wearable Devices Based on Biocompatible AlN Piezoelectric Sensors for Multiple Biosignal Monitoring**

Increasing world population and average health expenditures create worldwide bottlenecks in health systems. Personalized health (pHealth) can be described as personal health planning using medical, wearable, or implantable devices and offers a promising solution to healthcare bottlenecks. Among the pHealth tools, wearable devices outperform medical and implantable ones since they provide uninterrupted, non-invasive, and unobtrusive health monitoring. Piezoelectric sensing is a well-developed technology with many advantages, such as self-powered operations, ease of integration, high sensitivity, and accuracy. Among piezoelectric materials, aluminum nitride (AlN) is one of the most popular choices thanks to its high electrical resistivity and breakdown voltage, as well as impressive acoustic properties. Moreover, AlN is a biocompatible material, and its fabrication procedure is CMOS-compatible.

In this work, we propose a wireless wearable device employing AlN piezoelectric sensors to extract multiple health parameters. To do that, we readopted a previously suggested sensor structure and fabricated AlN piezoelectric sensors to detect skin deformations due to physiological activities like respiration and heartbeat. First, a test bench was created with commercial electronics to analyze the sensor functionality and extract the heart rate (HR), heart sounds, and respiration rate (RR) of the volunteers using the pulse wave signals acquired from the suprasternal notch (SSN), carotid artery, and radial artery. Simultaneously, a 3-electrode ECG measurement was performed to have a reference signal and validate the sensor output. When ECG-estimated and piezo-estimated HRs are compared, the maximum deviation was found below 5 beats per minute (bpm), which is an acceptable error margin. Moreover, the carotid and radial HR estimations provide a higher linear correlation (0.99) than the SSN (0.81), showing that these arteries are better locations for more accurate HR estimation. In addition, the carotid artery and the SSN were used to extract RR. The extracted RR was compared with manually counted breath numbers, and a maximum deviation of 1 breath for each 100-second measurement was observed. Furthermore, heart sounds were extracted from the SSN, making it a unique position that can provide three vital parameters. We also performed tests to detect speech from the SSN and observed the fundamental speech frequency while monitoring HR and heart sounds simultaneously.

Then, we designed a low-power wearable device, 25 mm by 35 mm, for the AlN sensors and tested the device on the same measurement sites. Using a single sensor on the SSN, we were able to detect RR, HR, heart sounds, and swallowing events, demonstrating the sensor's multifunctionality. The SNN-extracted HR information was confirmed with a clinically validated blood pressure monitor. Later, radial- and carotid-extracted HRs were compared with the HR values obtained from the blood pressure monitor. Only a 1 bpm difference was observed for carotid-extracted HR, whereas radial-extracted HRs were equal. Additionally, RR was successfully obtained from the carotid artery. Afterward, two sensors were simultaneously situated on the radial and carotid arteries of one male and one female volunteer, and multiple acquisitions were performed to calculate pulse transit time (PTT). The results show that extracted PTTs are aligned with the literature. These health parameters are important not only to monitor one's physical health but also to evaluate mental health status, as heart rate variability can be derived from the heart sound signals, and it is used for applications like emotion recognition, as well as depression and stress-level assessment. The proposed wearable device consumes only 7.7 mW while continuously transmitting data via BLE. This corresponds to approximately 120 hours of uninterrupted working using a standard 3.7 V 250 mAh lithium polymer (Li-Po) battery.

The following paragraphs report the organization of this Ph.D. thesis:

**Chapter 1 (Introduction)**: This chapter discusses the problems we address in this work and provides an insight into the reader. The chapter starts with the problem statement and explains the healthcare system bottlenecks with reasons. Then, eHealth is described in detail to discuss how it may help to solve current healthcare problems. Afterward, wearable devices are presented for non-invasive and unobtrusive health monitoring. MEMS technologies enable low-cost and miniaturized sensors for wearable devices. Therefore, we present MEMS fabrication techniques and compare principal transduction mechanisms. Among them, piezoelectricity offers many advantages, and we describe them detailedly to provide the necessary background.

**Chapter 2 (State-of-the-Art)**: Fundamental information about piezoelectricity, common piezoelectric sensor materials, and health applications employing piezoelectric sensors are provided in this chapter. The properties, advantages, and disadvantages of the most common piezoelectric materials are discussed here. In addition, various piezoelectric sensors for health applications provided in the literature are investigated in detail. In brief, this chapter aims to provide the reader with the necessary background on piezoelectric wearable sensors and devices and discuss state-of-the-art.

**Chapter 3 (Fabrication of Bio-compatible AlN Piezoelectric Sensors)**: This chapter is dedicated to AlN piezoelectric sensor fabrication and characterization. The chapter starts with the delineation of the AlN sensor multilayer and shielding structures. Then, the step-by-step AlN sensor fabrication process is explained in detail. Biocompatible packaging and different connector options are also discussed here. Lastly, sensor characterization and connection process are presented.

**Chapter 4 (Wireless Wearable Device Design and Fabrication):** Chapter 4 introduces the custom wearable device. First, system-level architecture and analog front-end design are provided. Afterward, a printed circuit board (PCB) design and component selection for different parts are presented. Firmware development and optimization for analog-to-digital conversion (ADC) and data transfer using Bluetooth Low Energy (BLE) protocol are bestowed here. The wearable case design and 3D printing process are also explained in this chapter.

**Chapter 5 (Experimental Results and Discussions)**: This chapter presents the experimental results and discussions. Initially, the AlN sensor is tested with commercial electronics to investigate different body locations, acquire different biosignals, and reveal the sensor's full potential. Then, custom wearable device tests, characterization, and verification are provided. Furthermore, initial analysis and some feature extraction from the acquired biosignals are performed and discussed. Additionally, the meaning of the extracted features and how they can help to diagnose various diseases are discussed here. A comparison of the outcomes with the state-of-the-art is also presented at the end of this chapter.

**Chapter 6 (Conclusion and Future Perspectives)**: Finally, a summary of this work is provided in the last chapter. The experimental results are summarized, and important outcomes are underlined. Ultimately, the thesis is concluded with future perspectives.