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学 位 論 文 内 容 の 要 旨

博士の専攻分野の名称　博士（情報科学）　氏名　宣　妍

学 位 論 文 題 名

Study of Flexible Sensors Toward Internet of Things (IoT) Applications
（モノのインターネット (IoT) 応用に向けたフレキシブルセンサに関する研究）

The rapid development of the Internet of Things (IoT) and wearable devices has brought increased attention to flexible sensors for their unique capability to provide real-time, non-invasive monitoring on non-planar surfaces. The demand for IoT-compatible devices capable of collecting, processing, and transmitting data has made flexible sensors essential components in IoT systems. Flexible sensors, unlike traditional rigid silicon-based sensors, conform to dynamic surfaces, enabling precise data collection in complex environments. This adaptability has facilitated their application in areas such as electronic skin, wearable health devices, and human-machine interfaces.

The versatility of flexible sensors is largely due to their highly flexible and stretchable materials, allowing applications in fields from health monitoring to environmental sensing. Advances in material science and nanotechnology have enabled flexible sensors to measure physiological parameters such as heart rate and temperature, which enhances applications in telemedicine, personalized diagnostics, and real-time health monitoring. Additionally, flexible sensors are being integrated into smart home, city, and industrial systems, where they provide core functionality for IoT by enhancing data collection accuracy across a wide range of environmental and operational contexts.

To make further advanced sensor system based on flexible devices, this study aims to develop flexible sensors with high functionality, adaptability, and user comfort, thereby advancing their use in smart systems by proposing different materials, new fabrication process, and new concepts. The research focuses on three flexible sensors: an optical image sensor, a wireless electrocardiogram (ECG) sensor, and a pressure sensor for specific applications in optical imaging, health monitoring, and pressure distribution measurement, respectively.

The optical image sensor leverages $ZnIn_2S_4$ (ZIS) nanosheets combined with thin-film transistors (TFTs) to achieve imaging on curved surfaces. The ECG sensor, incorporating a Kirigami structure to improve breathability and wearable comfort, enables continuous cardiac monitoring during extended wear. Finally, the pressure sensor, using laser-induced graphene (LIG) and polydimethylpolysiloxane (PDMS) membranes, detects both positive and negative pressures, offering potential applications in industrial monitoring and aerodynamics. This research also investigates the integrated system of multimodal sensors and data processing algorithm to enhance their performance in complex environments, supporting a broader range of applications in IoT systems.

This thesis is organized into the following chapters, detailing the design, development, experimental results, and application potential of flexible sensors.

Chapter 1: This chapter outlines the importance of flexible sensors in IoT applications for the smart systems by introducing the state-of-art studies and challenges for future practical applications. Flexible sensors, capable of precise data collection on complex, dynamic surfaces, are suited for applications in electronic skin, wearable health devices, and human-machine interfaces. After discussing the background and the state-of-art studies in this field, the aim of this study is explained.

Chapter 2: This chapter details the development of an active-matrix flexible optical image sensor designed for imaging on non-planar surfaces. The sensor utilizes solution-processed ZIS nanosheets as photosensitive material and integrates InGaZnO TFTs to form an active matrix circuit, ensuring low power consumption and suppression of cross-tack between pixels. Experimental results show high light absorption within the 370-470 nm range, with stability maintained after 1000 bending cycles at a 0.85 cm radius. This sensor provides an innovative solution for non-planar imaging, suitable for biomedical imaging and environmental monitoring.

Chapter 3: This chapter describes the design and optimization of a wireless ECG sensor. The study developed a breathable and flexible ECG sensor to meet the requirements for long-term, real-time cardiac monitoring. The sensor employs a Kirigami structure, enhancing breathability and wearable comfort owing to mechanical stretchability, with wireless data transmission via Bluetooth. The results indicate that this design provides a high signal-to-noise ratio in various movement states, with an optimal configuration of 1.5 cm electrode spacing and 204 mm² gel area, enabling the sensor to capture high-quality ECG signals under various wearing conditions without compromising monitoring performance due to noise interference. Additionally, experiments further verified the sensor's stability during extended wear; even during intense physical activity, the signal remained stable. This design makes the sensor suitable for various health monitoring scenarios, providing accurate data support for activity tracking and personalized health management.

Chapter 4: This chapter covers the development and application of a flexible air pressure sensor using laser-induced graphene (LIG) and PDMS membranes, designed to monitor both positive and negative pressures. A sealed air chamber beneath the LIG/PDMS layer enables real-time pressure distribution measurement on non-planar surfaces, addressing limitations of rigid MEMS sensors. Optimizing the PDMS membrane thickness allows the sensor to maintain high sensitivity with sensitivities of 10.2 %/kPa for negative and -0.55 %/kPa for positive pressures calculated by the sensor resistance change ratio per applied pressure. Tests on an aircraft wing model demonstrate the sensor' s effectiveness in providing pressure distribution under varied airflow conditions, confirming its applicability in IoT and aerospace.

Chapter 5: This chapter summarizes the main findings, showcasing flexible sensors' innovation and applicability in health monitoring, optical imaging, and pressure measurement. The optical image sensor enables imaging on curved surfaces; the ECG sensor offers a comfortable, accurate solution for long-term monitoring; and the pressure sensor innovatively uses LIG for bidirectional pressure detection, ideal for fluid dynamics and aerodynamics applications. This research highlights the immense potential of flexible sensors in IoT applications, laying a foundation for the next generation of efficient, low-power, long-term monitoring systems. Finally, as a perspective, future direction based on my experimental on-going research to integrate sensors and data analyses using machine learning is discussed.