A Low-Cost Inkjet-Printed Heart Sound Sensor for Telehealth Application

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***Abstract*—Telehealth is gaining popularity for remote monitoring of patients especially in rural areas. Stethoscopes are widely used by healthcare professionals to listen to internal sounds of the body, such as the heart. Unlike conventional passive stethoscope, a digital stethoscope with embedded sound monitoring sensor can facilitate an easy access for heart sound monitoring. In this paper, we propose a novel approach for heart sound detection using a low-cost inkjet-printed sensor placed inside the stethoscope's tube. The sensor is capable of detecting vibrations caused by the heart and converting them into an electrical signal. The signal is then analyzed using digital signal processing techniques to extract the heart rate. The sensor consists of two parallel plates with a narrow gap region filled with hexagonal boron nitride (hBN) nanoparticle ink, a dielectric and charge trapping material. The sensor was fabricated using inkjet-printing onto a PET film substrate, and provide a low-power, flexible, and cost-effective solution, with a fabrication cost of $0.19 per unit. Experimental results demonstrate that the‘ proposed sensor is highly efficient, with an average power consumption of ∼275.4 nW. This work contributes to the field of inkjet-printed circuits and sensors, providing a green-friendly and high-functioning alternative to traditional expensive silicon-based approaches.**

***Index Terms*—stethoscope, inkjet-printed sensor, heart sound detection, digital signal processing, heart rate monitoring, medical devices.**

I. Introduction

Stethoscopes have been used for over 200 years to diagnose various medical conditions, including cardiovascular diseases. However, traditional stethoscopes have limitations in terms of sensitivity, accuracy, and particularly when it comes to detecting faint heart sounds or differentiating between similar sounds [1]. Moreover, traditional stethoscopes are not well suited for converting biosignals to electrical signatures and be integrated with network for remote diagnosis. Fig. 1 demonstrates a conceptual diagram of remote monitoring of patients with sensors embedded in stethoscope and diagnosis of patients' vital signs for telehealth applications. By utilizing ultra-low-power sensors, energy-efficient computing, and telemetry schemes, vital signals could be acquired with small-footprint lightweight sensor system, process the sensor data *in-situ* for feature-extraction and data compression, and finally, relay the data wirelessly without overburdening the existing network bandwidth to a remote data center for further diagnosis or big data processing [2]–[9]. A cyber-physical platform will enable real-time remote patient data monitoring, processing,

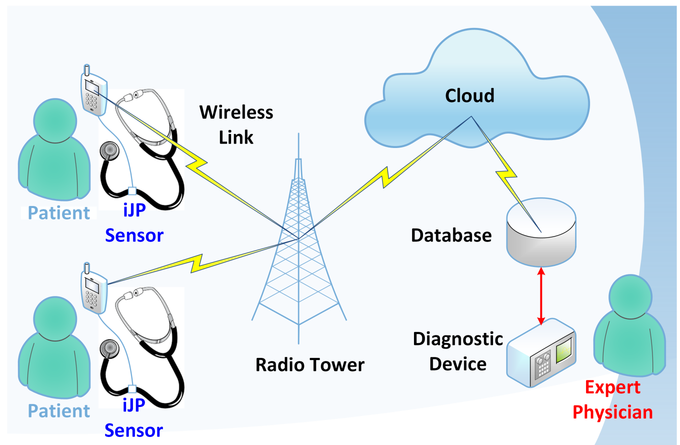

Fig. 1. Concept diagram of the inkjet-printed (iJP) sound sensor embedded within a stethoscope's tube for the potential telehealth applications.

and decision making process for the next-generation connected community.

In recent years, there has been increasing interest in developing novel sensors and computer processing technologies that can improve the performance of stethoscopes [10]–[12]. Several sensor technologies have been explored for remote monitoring applications, including remote sensor node for structural health monitoring [13], inkjet-printed soft resistive pressure sensor patch [14], [15], paper-based inkjet-printed Graphene sensor for breath monitoring [16], [17], inkjet-printed flexible temperature sensor [18], digital stethoscope [19], microcantilever array for pressure measurement [20], sensor signal readout systems for implantable devices [21]–[26], etc. A short list of commercial vibration or proximity sensors are listed in Table I. However, the conventional sensors are expensive, bulky, not suitable for rapid prototyping and environmentally green, and overall, challenging for massive-scale deployment. Out of several other sensor fabrication schemes, inkjet-printed sensors have emerged as a promising technology due to their low-cost, flexibility, and ease of fabrication.

Inkjet-printing is an affordable technology where nanoparticle-based inks can be patterned on a rigid or flexible substrate for manufacturing electronic devices and sensors. Unlike traditional clean-room fabrication, the material

TABLE I
VARIOUS TYPES OF COMMON PROXIMITY SENSORS

Sensor Type	Description
Capacitive Proximity Sensors	Senses changing capacitance.
Inductive Proximity Sensors	Senses changing inductance, includes RFID-based sensors.
Photoelectric Sensors	Senses changing photonic (light) exposure.
Ultrasonic Sensors	Senses high-frequency sound waves.
Magnetic Proximity Sensors	Senses changing magnetic fields.
Piezoelectric Sensors	Senses changes in mechanical strain.
Hall-effect Sensors	Uses the Hall effect to detect magnetic fields.

utilization in inkjet-printing is almost 100%, making it an ideal choice to utilize exotic nanomaterials for device fabrication. Inkjet-printed sensors and devices are widely reported for various applications ranging from respiration monitoring [17] to pressure mapping [27]–[31], artificial neuron [32], energy harvesting [33], etc. Successful inkjet-printing depends on the printing mechanisms (e.g., thermal, piezoelectric), composition of inks (e.g., water, alcohol) and the substrate. Unlike commercial expensive nanoparticle printers, a standard office inkjet-printer can also be configured by refilling the cartridges with nanoparticle-based inks for inkjet-printing of electronic devices and sensors [17], [27]–[29], [32].

In this work, we propose a low-cost affordable inkjet-printed sensor placed inside a stethoscope's tube for heart sound detection. In this paper we present the design and implementation of the inkjet-printed sensor and provide experimental results demonstrating its effectiveness in detecting heart sounds. To extract the heart rate from the sensor output, we used digital signal processing techniques to filter and analyze the signal. The resulting signal was then used to calculate the heart rate using algorithms such as peak detection or autocorrelation. To evaluate the effectiveness of our approach, we conducted experiments to compare the performance of our inkjet-printed sensor with a traditional stethoscope. The results show that our sensor was able to detect heart sounds with a high degree of accuracy and consistency.

The organization of the paper is as follows. First, inkjet-printed technology is introduced (Section II) and the fringe-field capacitance (FFC) sensor working principles are explained in Section III, followed by an explanation of the device fabrication in Section IV. The testing conditions and methods are defined in Section V and the results are shown and discussed in Section VI. Lastly, a discussion with future planned research is elaborated in Section VII and a conclusion is drawn in Section VIII.

II. INKJET-PRINTED TECHNOLOGY

The inkjet printed (IJP) technology, which utilizes piezoelectric printer dynamics to eject unique nanoparticles from a print head onto a substrate. This approach enables the creation of flexible, biodegradable, repeatable, highly inexpensive, and fast circuits, and sensors with a wide range of sensing applications, depending on the choice of materials and circuit structure [34]. The basic IJP process involves the steps as seen in Fig. 2. Initially, the refillable cartridges of the inkjet printer are filled with nano-particle inks. Afterward, a substrate is selected, which may be pretreated to enhance ink adhesion before printing. In some cases, commercially available pretreated substrates are utilized, as in the present study (see Section IV). The desired print patterns are created on a digital editing program, followed by printing the pattern layer-by-layer onto the substrate. Between each layer, the substrate can be thermally cured to enable continuous bulk formation of the nano-particles. Previous studies have utilized this simplified fabrication process to create sensors for various applications, some of which are cited in the references [17], [28], [29]. The fabrication process can differ based on research needs and may involve complex and costly procedures or equipment, such as plasma and gas treatment, non-inkjet printing ink deposition, spin-coating, magnetron sputtering, slot-die coating, precise parameter control, usage of new materials, and other customized techniques [35].

III. WORKING PRINCIPLE OF THE PROPOSED SENSOR

The equivalent capacitive circuit for two parallel silver plates inkjet printed onto a substrate is shown in Fig. 3. The capacitance formed between these two parallel printed lines can be represented by the famous Palmer's equation. The total capacitance manifests a constant lateral capacitance, C_l, and a fringe capacitance, C_f.

The C_f varies due to the presence of vibration being propagated through the substrate and creates a dynamic current flow to balance the charge equation.

$$i = \frac{dQ}{dt} = V \times \frac{dC_f}{dt} \quad (1)$$

When a voltage is applied in the capacitor model of inkjet printing (IJP), it generates an electromagnetic field (EMF). However, the EMF of the IJP capacitor exists beyond the plane of the substrate. As a result, the capacitance of the IJP capacitor varies based on how the EMF is affected by physical interference. The IJP sensor operates on low voltage supply

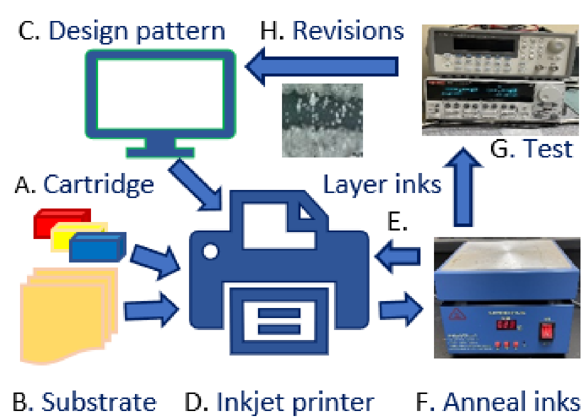

Fig. 2. Generic fabrication process using the IJP setup.

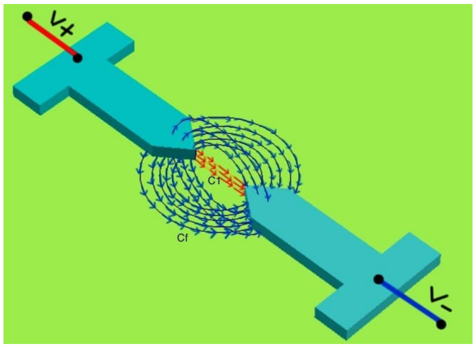

Fig. 3. The working principle of the IJP capacitor involves emitting a small electromagnetic field (EMF) that results in a change in charge when it is touched, bent, or deformed.

and current output, which results in a small EMF of the IJP capacitor, reducing unwanted interference.

IV. Inkjet-Printed Sensor Fabrication

The sensor fabrication was carried out at the Bioinspired Integrated Circuit Design (BIC) laboratory at UAB, as illustrated in the Fig. 4. The IJP FFC sensor consists of parallel plates of silver (Ag) nanoparticles that are printed onto a polyethylene terephthalate (PET) film using a standard drop-on-demand, piezoelectric printer. To avoid channel shorting caused by ink splattering, the silver parallel plates are printed with a gap of roughly 0.8 mm, which is selected to be above the printer's minimum resolution of 0.3 mm. After printing, the ink is annealed by positioning the sensor on a hot plate at 60 °C for 4 minutes. In the fabrication process, an ink made of Hexagonal Boron Nitride (hBN) is deposited onto the channel region of the terminals. This material acts as a dielectric and charge trapping substance. After drying the ink by curing on a hotplate for 4 minutes at 60 °C, a small cut is made along the gap using a blade. This cut is made to improve the charge trapping abilities of the hBN material and enhance the sensor's sensing behavior.

The samples printed for this work have a substrate thickness of 135 μm and costs $180 (NB-TP-3GU100 Mitsubishi Paper Mills) for 100 sheets ($1.80/sheet or $0.09/sample at 20 samples per page). The cost to print is estimated from a 100 mL bottle of silver nanoparticle ink costing $120 (NBSIJ-MU01 Mitsubishi Paper Mills) at 220 pages per 11 mL cartridge ($0.0027/sample), and 5 mL bottle of hBN ink (Sigma Aldrich 901410-5ML) costing $225 ($0.102/sensor). The total estimated cost for each sensor is $0.19 per sample. The printer and cartridges are one-time costs and not considered in the cost estimation, making the substrate the most expensive component of each sample. Replacing the PET film with photo-paper would reduce the cost even further.

V. Testing Parameters and Conditions

A stethoscope works by transmitting sound waves from the chest piece through hollow tubes, which are air-filled structures that enable the transmission of sound energy to the listener's ears [1]. In our experiment, we modified the

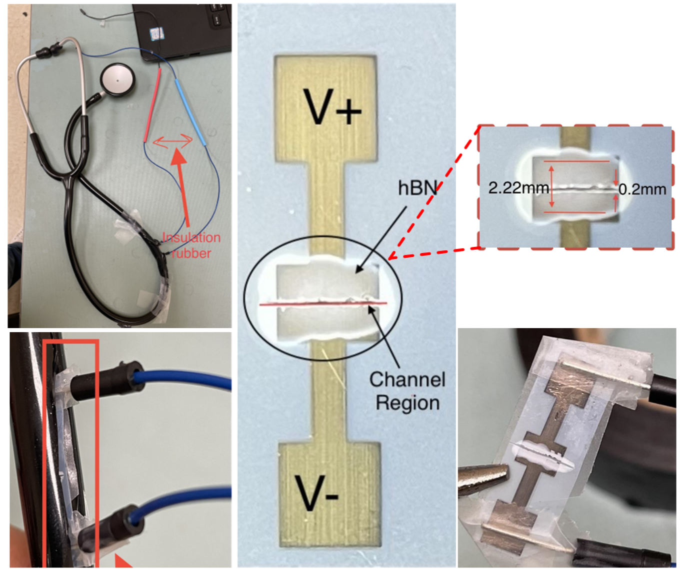

Fig. 4. The design of the IJP FFC Sensor includes various materials, as depicted in the diagram. A cut was made along the gap region, represented by a red line, to define the gap length and improve the charge trapping abilities, thus enhancing the sensor's sensing behavior.

stethoscope by inserting an inkjet-printed sensor into the center of the stethoscope tube to capture the heart pulse. To do this, we made a cut of length 29 mm at the center of the tube and then sealed the cut with insulation tape to prevent any air leakage. Three designs were experimented with, the first being the sensor illustrated in Fig. 4, while the others design was not presented in this study. While it is possible to generalize about FFC sensors based on other samples, a comparison of the test results for the three sensors reveals that the gap length of the FFC sensors affects their sensitivity. Specifically, a longer gap length results in more charge trapping, leading to higher fringe field capacitance.

VI. Testing Results

We conducted several tests to collect data on the sensor's performance. These tests involved placing the chest-piece of the stethoscope both on and off the chest and collecting data for various voltage ranges, including 3.3 V, 5 V, 10 V, 20 V, and 24 V. The voltages were selected based on the common voltage supply ranges for contemporary electronics. This selection enables the potential integration of the sensor with microcontrollers and ASICs in future. During the tests, the sensor collected sound waves from inside the stethoscope tube and converted them into output current signals. We then compared the sensor output current at 60 Hz with a Keithley 2604B SourceMeter. All the data collections were carried out using KickStart software package and post-processed the data. A student in the lab volunteered, and Figs. 5 and 6 show the time series of data of the prototype sensor embedded into the stethoscope's tube with chest-piece on the chest with heart beat sound. For validation, the ear-piece was used to hear the heart beat sounds. On average, the current output was ~13.77 nA at 20 V, resulting in an average power of ~275.4 nW.

Applying lower voltages resulted in lower current output and significantly decreased the average power.

Fig. 5 captures the noisy signal but it clearly depicts the sensor performance to capture the heart beat sound. To extract the heart beats from the time-series data, a post-processing scheme is applied. As shown in Fig. 6, a time-windowed data frame (e.g., 10 sec to 15 sec time-window) is taken first (Fig. 6(a)), normalized the sample-to-sample difference of the signal (Fig. 6(b)), and finally, a 10-point moving rms is applied on the data (Fig. 6(c)), where periodic pulses indicate the heart beats with time. The measured 60 beats/min (approx.) complies with the heart beats of a healthy individual.

VII. Discussion and Future Work

The fabrication process of FFC sensors is subject to inconsistencies, which can arise due to factors such as the volume of hBN applied, curing distribution, and quality of the cut channel region. While sensing behavior is consistent across all tests, human error can lead to subtle variations in sensor biasing. The concentration of hBN ink drop, which can range from 1-2 µL, can cause slight variations in current averages due to differences in ink thickness after curing. Additionally, the curing process may suffer from the ring effect, leading to higher concentrations of nanoparticles at the edges. The quality of the channel region cut is dependent on blade sharpness and cut depth control, which determines the cut's width and length. Larger area cuts can alter the capacitor's fringe-field and affect its sensitivity. Automating the hBN application and channel region cut can lead to more consistent sensor biasing.

The FFC's sensitivity can be easily adjusted by modifying the channel width to length ratio for optimized power utilization. The applied voltage and minimal power usage make it compatible with microcontrollers, but signal boosting may be required for analog to digital conversion. Future work includes a study on longevity and durability, as well as integration with microcontrollers.

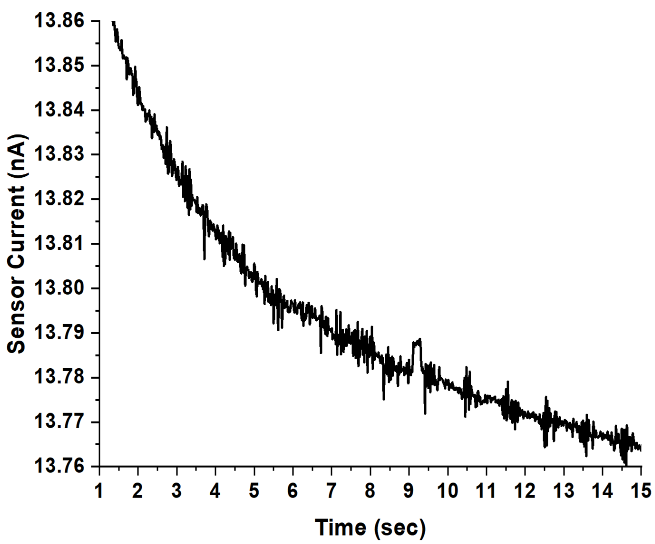

Fig. 5. The sensor output current variations over time with heart beat sounds. The periodicity of signal bursts correlates with the human heart beats.

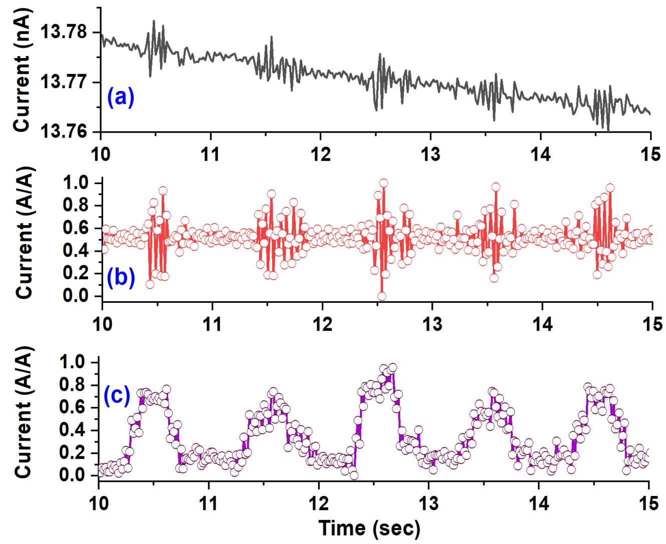

Fig. 6. Post-processing scheme. (a) Time-windowed data. (b) Normalized sample-to-sample difference of the time-windowed data. (c) Normalized 10-point moving rms of the signal in (b). The plot shows distinct pulses to indicate the heart beats.

The prototype low-cost inkjet-printed sensor using commercial printers will enable an affordable sensor fabrication scheme on paper or plastic films to transform passive diagnostic devices such as a stethoscope, into active sensing nodes or edge devices for next generation internet-of-things and telehealth applications. The prototype sensor integrated with smaller footprint wireless microcontroller or custom radio-frequency application specific integrated circuits (RF-ASIC) along with small battery pack will not add significant weight and obnoxious physical appearance to the diagnostic devices.

VIII. Conclusion

The paper proposes a novel approach for heart sound detection using an inkjet-printed sensor placed inside the stethoscope tube. The inkjet-printed sensor can detect vibrations caused by the heart and convert them into an electrical signal that can be analyzed using digital signal processing techniques to extract the heart rate. Experimental results demonstrate that the proposed sensor is highly efficient, with an average power consumption of $\sim$275.4 nW and provides a more accurate and objective measurement of heart sounds compared to traditional stethoscopes. The inkjet-printed sensor is low-cost, flexible, and easy to fabricate, making it a practical solution for heart sound detection in clinical settings. The paper concludes that the inkjet-printed sensor can be easily integrated into existing stethoscopes, providing an upgrade to traditional devices that can improve the accuracy of cardiovascular disease diagnosis.

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