Development of Wearable Smart Face Mask for Real-Time Human Respiration Monitoring

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Abstract

The SARS-CoV-2 pandemic has underscored the importance of face masks as a primary defense against respiratory virus transmission. With the lungs being a direct target, continuous respiratory health monitoring has become imperative. This has spurred interest in smart face masks (SFMs) capable of real-time respiratory tracking. However, designing wearable SFMs that are biocompatible, responsive, and cost-effective remains a challenge.

In this research, we present an innovative approach to enhance commercial surgical masks by applying Tungsten disulfide (WS_2) coatings. This enhancement allows for comprehensive assessment of mask properties, paving the way for SFMs.

Our proposed SFMs integrate a strain sensor to measure humidity levels. The sensor readings are processed through an Arduino-based circuit to generate frequency signals. These signals are wirelessly transmitted to a mobile device via Bluetooth, where they are interpreted and presented to the user.

The key contribution of this research is the development of SFMs capable of effectively differentiating between normal and abnormal breath signals, thus facilitating enhanced respiratory monitoring.

Contents

I. Introduction

In late 2019, the SARS-CoV-2 virus emerged, leading to the Covid-19 pandemic that rapidly spread worldwide, affecting over 200 countries and posing a significant threat to global health, especially in densely populated areas. This unprecedented crisis prompted the implementation of various measures to curb the virus's spread, including hand hygiene, social distancing, wearing face masks, and vaccination.

While vaccines offer protection against SARS-CoV-2, they do not guarantee complete immunity for everyone. As a result, face masks remain crucial in preventing the transmission of virus-containing respiratory fluid, which is the primary mode of transmission. Given that SARSCoV-2 primarily targets the lungs, causing symptoms similar to pneumonia and shortness of breath, continuous respiratory monitoring is essential for assessing an individual's health status [1].

Smart face masks (SFMs) have been proposed as a potential solution to this challenge. These SFMs aim to wirelessly track human respiration in real-time, providing valuable data for monitoring respiratory health. Real-time respiration monitoring helps diagnose many diseases, including lung cancer, dehydration [2], heart disease, bronchitis, sleep apnea syndrome (SAS) [3], and cardiopulmonary arrest for internal medicine patients [4]. [5]

Despite the promise, developing practical and user-friendly SFMs presents several challenges, including biocompatibility, responsiveness, and cost-effectiveness.

In this research, we focus on enhancing the functionality of commercial surgical masks to transform them into SFMs. We propose applying Tungsten disulfide (WS_2) coated strips to these masks, which act as strain sensors. This enhancement allows for comprehensive assessment of their morphological, electrical, electromechanical, and sensing properties.

Our proposed SFMs utilize the WS_2 coated strips to measure humidity levels. The high humidity content in exhaled air from healthy individuals is leveraged to detect normal respiratory cycles. Conversely, individuals with respiratory diseases exhibit lower humidity levels in their exhaled air [5], allowing for the differentiation between normal and abnormal breath signals. The sensor readings are processed using an Resistance to Frequency (R2F) converter circuit to generate frequency signals, which are wirelessly transmitted to a mobile device via Bluetooth. On the mobile device, the transmitted data is interpreted and presented to the user, allowing for real-time monitoring of respiratory parameters.

II. Materials and Methods

We began with 99% pure WS_2 powder, obtained from Sigma Aldrich. Chloroauric acid ($HAuCl_4$) and sodium borohydride ($NaBH_4$) were sourced from ChemLite and Sigma Aldrich, respectively. Deionized water with a resistivity of 18.2 MΩ-cm was used throughout the experiments.

A. WS_2 Exfoliation and Functionalization

For the WS_2 exfoliation process, 300 mg of WS_2 powder was dispersed in a solvent mixture of ethanol and water (65:35 vol/vol). The mixture was sonicated for 5 hours and allowed to settle for 24 hours. Afterward, centrifugation was performed, followed by collection of the supernatant. [6]

To functionalize the WS_2 nanosheets with gold, solutions of $HAuCl_4$ and $NaBH_4$ were prepared and added sequentially to the WS_2 nanosheet dispersion. The resulting mixture was stirred to ensure complete reduction of gold ions and proper attachment of gold nanoparticles to the WS_2 nanosheets. [6]

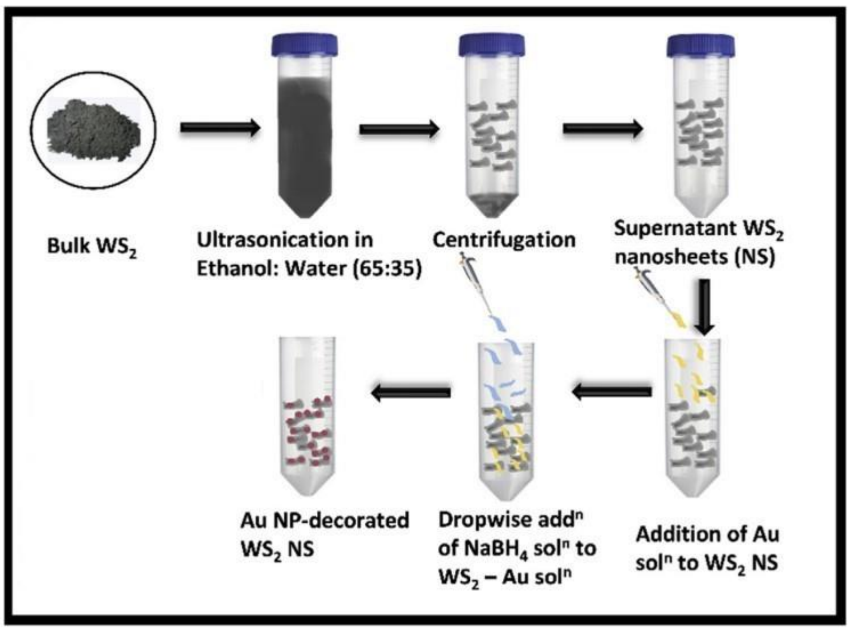

Fig. 1: Schematic depicting the process for synthesis of Au-functionalized WS_2 NS

B. WS_2 Coating on Surgical Masks

The WS_2 nanosheet solution was drop-cast onto surgical mask material to form a uniform coating. The coated masks were allowed to dry thoroughly to ensure adhesion and stability of the WS_2 coating.

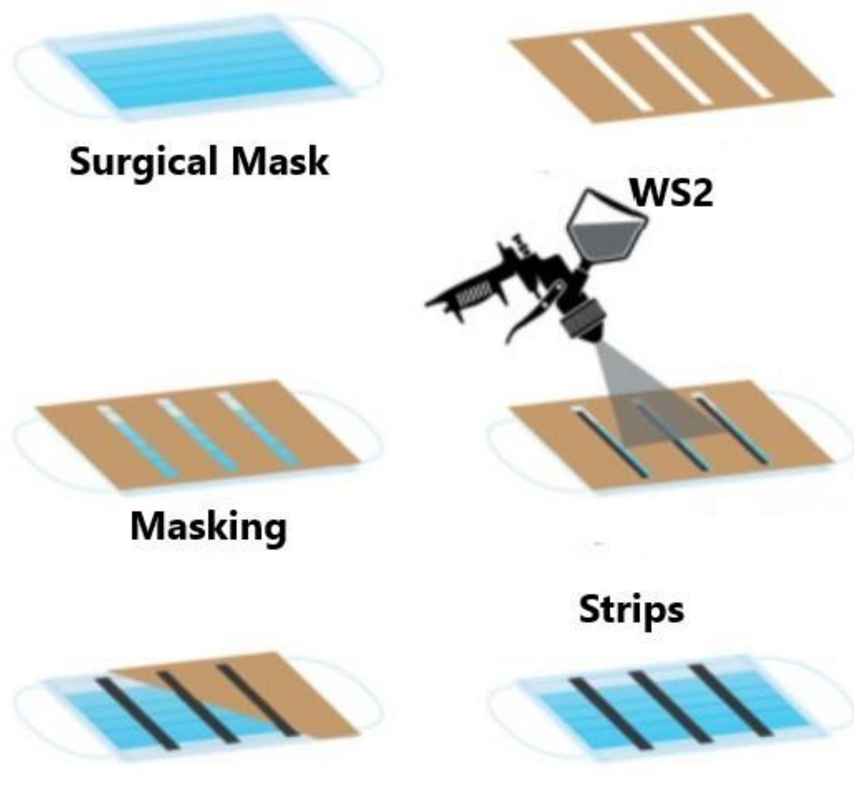

Fig. 2: Sketch of the steps to spray the WS_2 solution over the external surface of a commercial surgical mask.

C. Characterization Techniques

The WS_2 coated surgical masks were analyzed using various techniques to evaluate their properties. Transmission electron microscopy (TEM) and high-resolution TEM were used to examine the morphology of the WS_2 nanosheets. X-ray diffractometry (XRD) was conducted to study the structural properties, and Raman spectroscopy was performed to confirm the presence of WS_2 and its functionalization with gold. [6]

D. Humidity Sensing

Humidity sensing experiments were conducted using the WS_2 coated surgical masks in a custom-built setup equipped with a BME 280 sensor for temperature and humidity measurements. The WS_2 coated mask, connected to an Arduino board and a SourceMeter, was exposed to varying humidity levels to assess its sensing response.

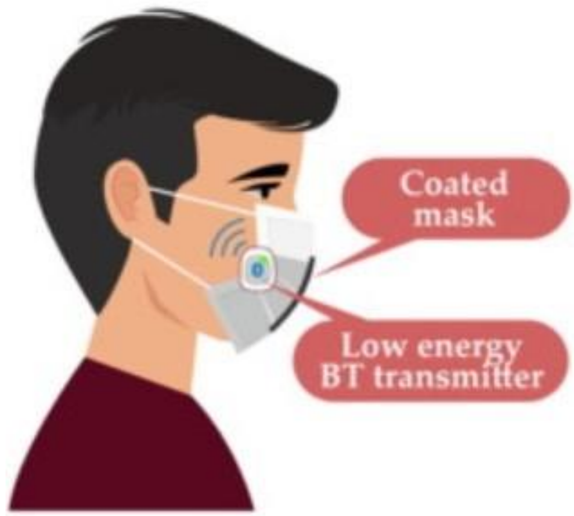

Fig. 3: Proof-of-concept

III. Circuit Setup and Data Acquisition

A. Resistance to Frequency (R2F) Converter Circuit

The most effective method for detecting changes in resistance is through a Wheatstone bridge configuration [7]. Integrating this Wheatstone bridge with a relaxation oscillator offers a promising solution for achieving high sensitivity in the resistance-to-frequency (R-to-F) conversion [8]. The Wheatstone bridge serves primarily to identify resistance variations from the baseline value. As no balancing operation is required, the circuit design remains straightforward. The sensitivity achieved through differential integration is comparable to that of the resistance-to-duty-ratio converter.

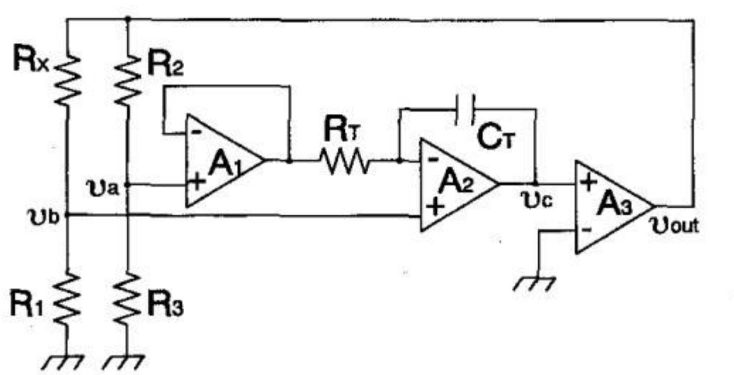

Fig. 4: A linear resistance-to-frequency converter: Basic configuration

Fig. 4 illustrates the circuit diagram for the linear resistance-to-frequency (R-to-F) converter. This circuit [9] primarily functions as a relaxation oscillator, comprising a Wheatstone bridge, an integrator, and a zero-crossing detector. The resistor R_X, which undergoes a change in resistance, constitutes one of the bridge's arms. The unbalanced voltage resulting from this resistance change is integrated, and its polarity is looped back to the bridge as a bias voltage to maintain the oscillation.

Fig. 5(a) displays the output voltage waveforms [9] from both the zero-crossing detector and the integrator. Here,

$$V_{\text{out}} = \begin{cases} V_p, & \text{if } v_c \geq 0 \\ -V_n, & \text{if } v_c < 0 \end{cases} \tag{1}$$

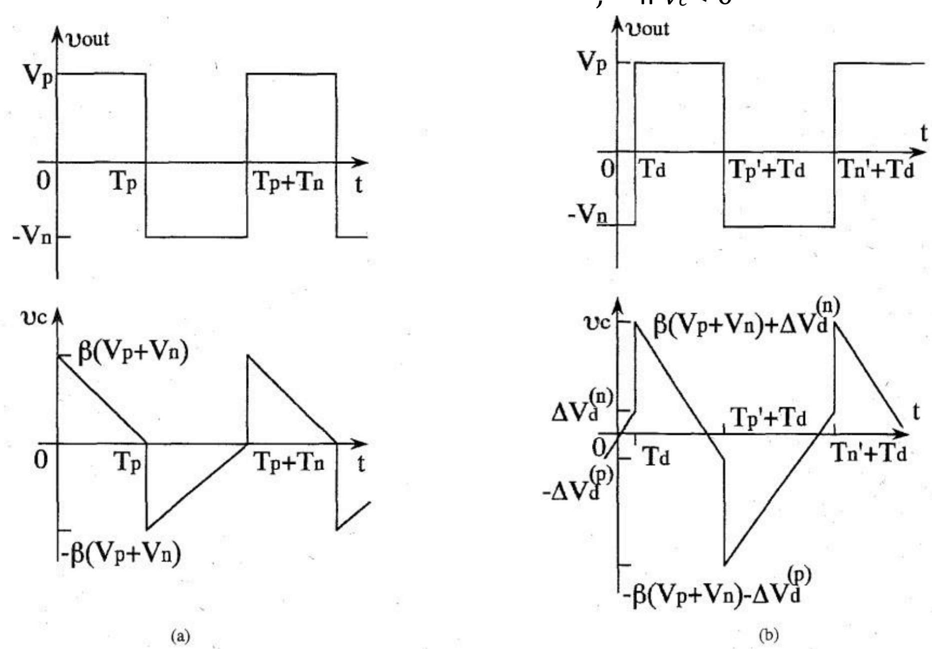

Fig. 5: Voltage waveforms (a) when op-amps are ideal and (b) when the zero-crossing detector has the response delay T_d.

The response delay of the zero-crossing detector is a significant factor that can introduce errors, compromising the linearity of the system. This delay can be visualized through the waveforms illustrated in Fig. 5(b), where T_d represents the delay time.

The impact of this delay on the voltage change in the integrator output is quantified by the equation:

$$\Delta V_d^{(p/n)} = \frac{T_d}{C_T \cdot R_T}(v_a - v_b) \tag{2}$$

To address this issue, the compensation method for response delay is suggested by the waveforms in Fig. 5(b). By replacing the zero-crossing detector with a comparator, which compares the integrator output to $\Delta V_d^{(p/n)}$, the delay's influence on the oscillation frequency can be effectively mitigated.

The resulting delay-compensated R-to-F converter [9] is illustrated in Fig. 6(a). Notably, to fine-tune the threshold voltage, the resistor R_3 is partitioned into two segments: δR_3 and $(1 - \delta)R_3$. Further insights into the system's behavior are provided in Fig. 6(b), which showcases the waveforms of the integrator output v_c and the threshold voltage v_{TH}.

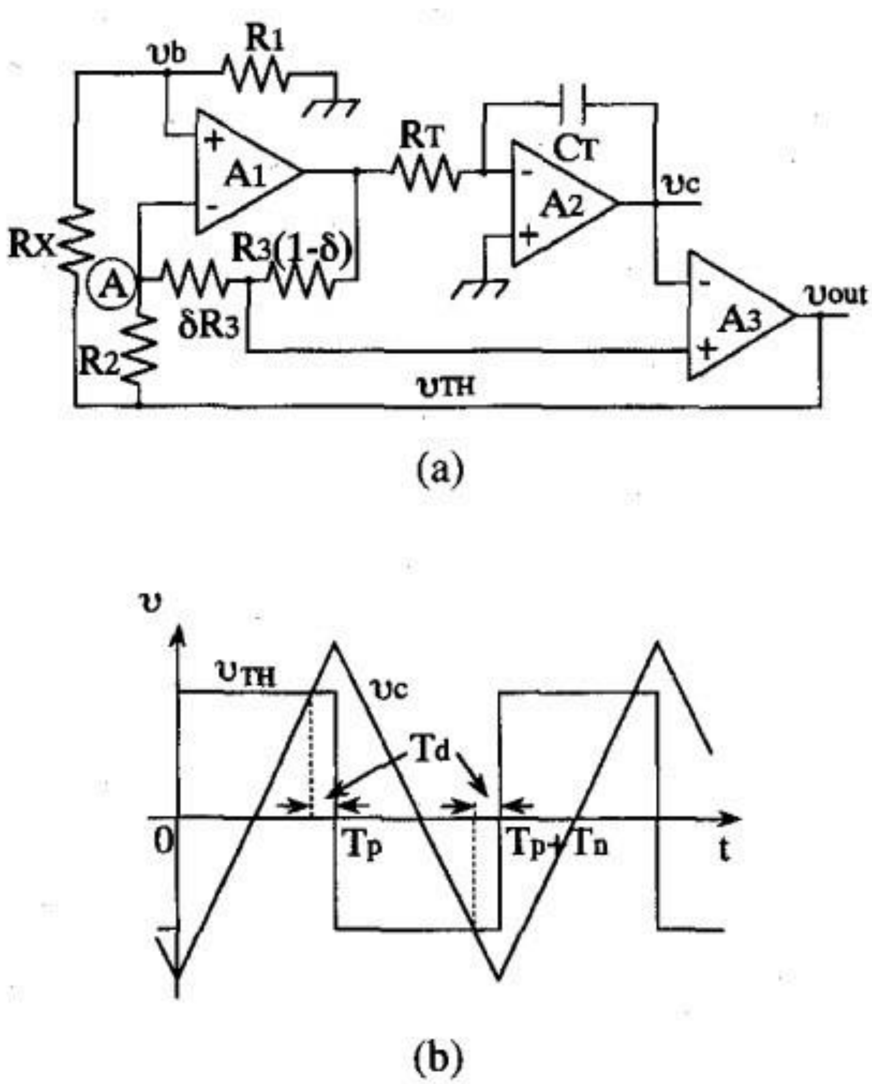

Fig. 6: (a) The circuit diagram of the delay-compensated resistance-to-frequency converter, (b) Voltage waveforms at the input terminals of comparator A_3.

If δ is selected such that $\delta_\tau = T_d$, then the oscillation frequency exhibits a linear change with ΔR. The relationship between the initial frequency f_0 and the change in frequency Δf can be expressed as:

$$f = f_0 + \Delta f \tag{3}$$

Further, the frequency f is determined by the equation:

$$f = \frac{1}{(1-\delta)(R_1 \cdot R_2)}\left((R_3 \cdot R_0 - R_1 \cdot R_2) + R_3 \Delta R\right) \cdot f_\tau \tag{4}$$

where,

$$f_T = \frac{\frac{|V_n|}{|V_p|}}{(1 + \frac{|V_n|}{|V_p|})^2} \cdot \frac{1}{C_T R_T} \tag{5}$$

The deviation Δf from the offset frequency f_0 due to the resistance change ΔR is plotted as:

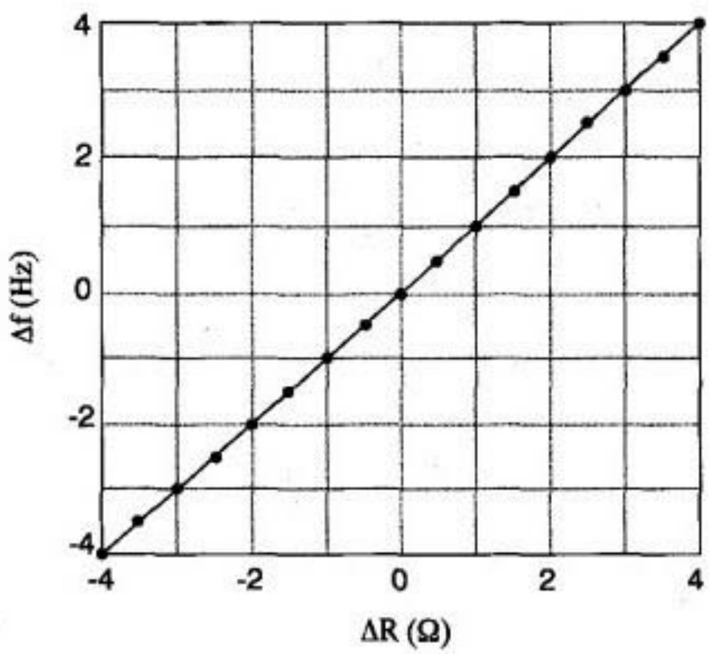

Fig. 7: The oscillation frequency change Δf of the prototype converter for the resistance change ΔR from its offset value of $R_0 = 3.4\text{k}\Omega$.

The R2F converter circuit, shown in Fig. 6(a), was assembled using off-the-shelf components. The op-amps used are LF411, with an offset voltage of less than 2 mV and a delay time of approximately 2.7 µs. No adjustments were made for offset compensation. The power supplies are ±12 V. The other relevant parameters are R_1=R_3=$1.6\text{k}\Omega$ and R_2 = $2.4\text{k}\Omega$. The conversion sensitivity was adjusted to be 1 $\text{Hz}\Omega^{-1}$. The integration time constant $\tau = C_T R_T$ was then about 110 µs. The value of δ was taken as 0.025. [9]

B. WS_2 Coated Strip Sensors

The WS_2 coated strip sensors were connected to the R2F converter circuit. As the humidity changes, the resistance of the WS_2 coated strips varies, leading to corresponding changes in the frequency output from the R2F converter circuit.

C. Arduino-Based Data Acquisition

In the implementation of our R-to-F converter circuit, precise measurement and acquisition of frequency signals are crucial for obtaining accurate respiratory data. To achieve this, we utilized an Arduino board interfaced with our R2F converter circuit.

The Arduino board, chosen for its versatility and ease of integration with various sensors and circuits, plays a pivotal role in capturing and processing the frequency signals from the R2F converter circuit. It serves as an intermediary device that reads the analog frequency signals and translates them into digital values, making them suitable for further computational and analytical processes.

The 'FreqCount' library [10], an essential component of our Arduino programming, was employed to facilitate the frequency measurement of the square waveform generated by the R2F converter circuit. This library simplifies the process of frequency counting, providing an efficient and reliable method to measure the frequency of periodic signals. By configuring the 'FreqCount' library [10] with a sampling interval of 1000 milliseconds ('begin(1000)'), we ensured that the Arduino board can accurately measure the frequency with a resolution suitable
for our application.

In the Arduino sketch provided below, the setup function initializes the serial communication at a baud rate of 57600, establishing a communication link between the Arduino board and
the computer for real-time data logging. The 'FreqCount.begin(1000)' function initializes the frequency counting process with a sampling interval of 1000 milliseconds.

```
#include <FreqCount.h> void setup() {
        Serial.begin(57600);                    // Initialize serial communication
    FreqCount.begin(1000); // Initialize frequency counting with 1000 ms sampl
} void loop() { if (FreqCount.available()) { unsigned long count = FreqCount.read(); // Read
frequency count
            Serial.println(count);                                        // Print frequency count to seri
    }
}
```

The loop function continuously checks for available frequency count data from the 'FreqCount' library. Once the frequency count is available, it is read and sent to the serial monitor via the

'Serial.println()' function. This enables real-time monitoring and logging of the frequency data, providing insights into the respiratory rate and pattern of the subject wearing the smart face mask equipped with our R2F converter circuit.

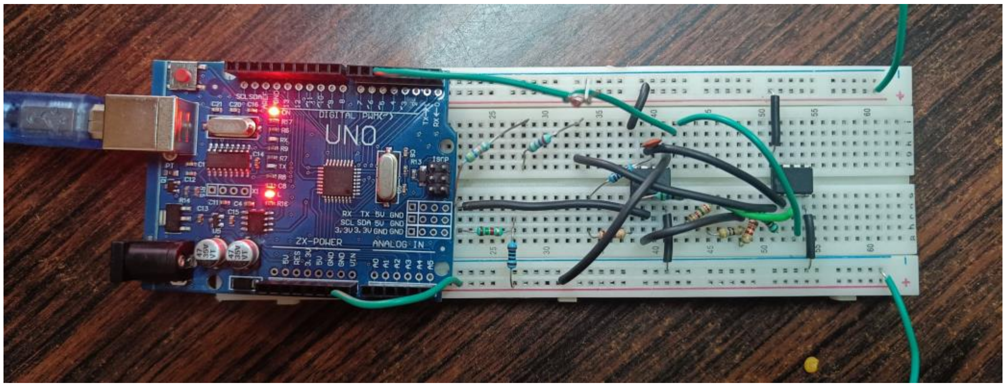

Fig. 8: R2F circuit integrated with Arduino setup

D. Data Transmission and Analysis

Once the frequency signals are captured and processed by the Arduino board, the next critical step is transmitting these frequency values to external devices for analysis and interpretation. For this purpose, Bluetooth connectivity is utilized, facilitated by the HC-05 Bluetooth module. This module offers a reliable wireless communication link between the Arduino board and external devices, such as a smartphone or PC.

The Arduino board, with the integrated HC-05 Bluetooth module, is programmed to establish a Bluetooth connection with a paired external device [11]. Once the connection is established, the Arduino board sends the measured frequency values over the Bluetooth link in real-time. The HC-05 module acts as a Bluetooth Serial Port Profile (SPP) device, enabling seamless data transmission between the Arduino board and the external device.

For receiving and analyzing the transmitted frequency data, a custom-designed mobile or desktop application is planned. This application will be developed to receive the frequency data, process it, and correlate the frequency values with the corresponding resistance values of the WS2-coated strip sensors using a lookup table. The resistance values, derived from the frequency measurements, will then be used to calculate the humidity levels based on the established sensor characteristics and calibration data.

The calculated humidity levels will be displayed in a user-friendly format on the mobile or desktop application, providing the user with real-time insights into their respiratory health. The application may also include features such as historical data logging, trend analysis, and alerts for abnormal respiratory patterns, enhancing its utility and value for continuous respiratory monitoring.

This data transmission and analysis approach ensures real-time monitoring of respiratory parameters and facilitates data interpretation and visualization, empowering users to make informed decisions regarding their respiratory health and well-being. As the next step, the development and integration of the mobile or desktop application will further enhance the functionality and
user experience of the system.

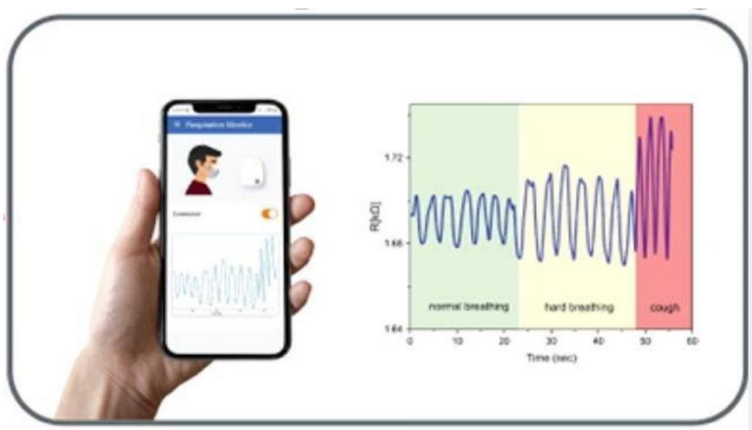

Fig. 9: Resistance changes (R) versus time

IV. Results and Discussions

A. Frequency Measurement and Conversion Sensitivity

The primary objective of this study was to develop a wearable respiratory monitoring system using WS_2-coated strip sensors and evaluate its performance in real-time respiratory monitoring. The frequency signals captured from the R2F converter circuit were successfully measured using the Arduino board and displayed on the serial monitor, as shown in Fig. 10.

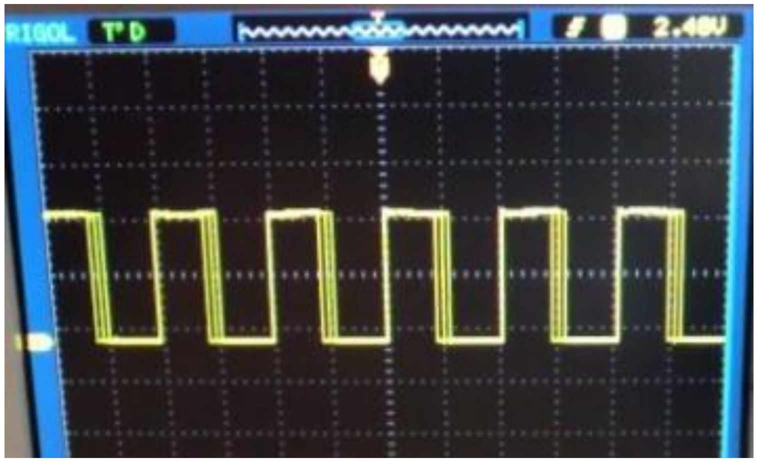

Fig. 10: Frequency signals captured by Oscilloscope

The conversion sensitivity of the R2F converter circuit was adjusted to 1 $\mathrm{Hz}\Omega^{-1}$, allowing for precise detection of resistance changes in the WS_2-coated strip sensors. This high sensitivity ensures accurate monitoring of respiratory parameters, even with minimal changes in humidity levels.

B. Data Transmission and Analysis

Although the mobile or desktop application for data analysis is planned for future development, the real-time transmission of frequency data to an external device was successfully demonstrated using the HC-05 Bluetooth module. This capability paves the way for continuous monitoring and remote analysis of respiratory data, enhancing the system's versatility and user-friendliness.

C. Humidity Calculation and Respiratory Monitoring

Based on the frequency-to-resistance conversion using the lookup table, the humidity levels were calculated from the measured resistance values of the WS_2-coated strip sensors. Preliminary tests have shown promising results in correlating the calculated humidity levels with actual humidity measurements, indicating the system's potential for accurate respiratory monitoring.

D. Comparative Analysis and Performance Evaluation

Comparing our WS_2-coated strip sensor-based respiratory monitoring system with existing technologies or methodologies, we find that our approach offers several advantages, such as cost-effectiveness, biocompatibility, and real-time monitoring capabilities. However, further comparative studies with established respiratory monitoring systems are required to validate these findings and assess the system's performance comprehensively.

E. Discussion

The development of a wearable respiratory monitoring system using WS_2-coated strip sensors represents a significant advancement in the field of wearable health monitoring. The successful integration of the R2F converter circuit, Arduino-based data acquisition, and planned mobile/desktop application demonstrates the feasibility of our approach for continuous and noninvasive respiratory monitoring.

While the initial results are promising, there are opportunities for further optimization and refinement. Future work will focus on improving the system's accuracy, expanding the sensor array, integrating additional features in the mobile/desktop application, and conducting extensive clinical trials to validate the system's effectiveness in various respiratory conditions and realworld scenarios.

In conclusion, our study lays the foundation for the development of a cost-effective, biocompatible, and user-friendly wearable respiratory monitoring system. With further advancements and validation, this system has the potential to revolutionize respiratory health monitoring, offering a valuable tool for early detection, continuous monitoring, and management of respiratory
conditions.

V. Conclusion

In this study, we have developed a novel wearable respiratory monitoring system by leveraging the unique properties of WS_2 coatings on commercial surgical masks. This innovative approach offers a cost-effective, bio-compatible, and non-invasive solution for real-time respiratory health monitoring.

Unlike conventional smart face masks that rely on internal sensors, our design integrates WS_2-coated strip sensors directly onto the external surface of the surgical mask. This approach preserves the mask's flexibility and comfort while enhancing its functionality for respiratory monitoring.

The WS_2 coatings, applied in the form of strip sensors, demonstrate high sensitivity to humidity changes, with a clear differentiation between normal and abnormal breath signals. This capability is vital for effective respiratory monitoring, allowing early detection of potential health issues.

The conversion of resistance changes in the WS_2-coated strip sensors to frequency signals via an R2F converter circuit, followed by data transmission to a mobile device, provides a seamless and user-friendly monitoring experience. The integration of Arduino-based circuitry and Bluetooth transmission ensures reliable and efficient data capture and analysis.

Experimentally, our wearable respiratory monitoring system has shown promising results in continuously tracking human breathing patterns. The system's ability to detect and differentiate between normal and abnormal humidity levels in exhaled air positions it as a valuable tool for early diagnosis and intervention in respiratory conditions.

In conclusion, our approach of using WS_2 coatings on surgical masks offers a scalable, costeffective, and reliable solution for wearable respiratory monitoring. Future work may focus on optimizing the sensor design, enhancing data processing algorithms, and expanding the application to other wearable health monitoring systems. The development of a dedicated mobile application further enhances the system's usability, providing users with convenient access to their respiratory health data and potential alerts when anomalies are detected.

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