

# Portable and wireless signal transducer for field testing of environmental monitors based on 2D materials

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**Abstract** — *In this paper we present the design and fabrication of a portable device for environmental monitoring applications. This novel hand-held apparatus monitors the changes in the resistance of a sensing surface with a high accuracy and resolution and transmits the recorded data wirelessly to a cellphone. Such a design offers a solution for field testing of environmental sensors. The tested sensing surface in this study is based on an ultrathin material: graphene, which is placed on the surface of a Si/SiO<sub>2</sub> wafer. This signal transducer and wireless communication system form together an ideal platform to harvest the sensitivity and selectivity of 2D materials for gas sensing applications.*

## I. INTRODUCTION

Environmental monitoring is paramount for the safety and security of workers in certain industries (chemical, petrochemical, mining etc.) as well as in the broader safety of citizens. Driven by the technological demands to embed electronics systems in flexible and wearable devices, environmental monitors must also be developed to be integrated with such novel technologies. The lack of bulk materials that are concomitantly bendable, highly sensitive and energy efficient, hinders the progress in developing products that can be compatible with the next generation of portable electronics. Graphene, which is the thinnest possible material, as well as other atomically thin layers of two-dimensional (2D) materials (MoS<sub>2</sub>, ReS<sub>2</sub>, etc.) are thought to be strong candidates for the next-generation of electronics and optoelectronics devices [1]. This is due to their mechanical strength and flexibility, and their high-electron mobilities, which lead to low-power consumption and unique transport properties enabled by confining electrons in 2D [2].

Although graphene-based sensors have already shown promise [3,4] more progress is needed to integrate them in monitoring systems. Specifically, the issue of field testing of 2D-material based sensors is yet to be resolved. Typical laboratory experimental set-ups used for testing sensor's performance are complex and cannot be deployed in a real-life testing situation, hampering progress toward development of 2D-materials based technologies.

Here we present a signal transducer and wireless communication system that is compatible with 2D material sensors and can be used in field testing. Our device advances the path towards adapting 2D material-based sensors for use in environmental monitoring systems.

## II. DESIGN

### A. Design of the portable apparatus

The portable apparatus developed in this work consists of several components represented schematically in Fig. 1. The whole system is powered by two batteries: a 3350 mAh lithium ion battery and a 1000 mAh lithium polymer battery, which are labeled *a* and *b* in Fig. 1, respectively. Together, they provide rechargeable and continuous power to the main circuitry (*c*) and the microcontroller module (*d*). To ease the recharging process, a module with a female micro-usb port (*e*) provides an easy interface to recharge the lithium ion battery. The lithium polymer battery can also be recharged via a female mini-usb port connected to the module of the microcontroller. The batteries provide a ripple-free DC voltage that reduces the electronic noise and ensures a higher sensitivity and cleaner read-out. The system is also equipped with two switches (*f*) allowing the user to manually turn off the device.

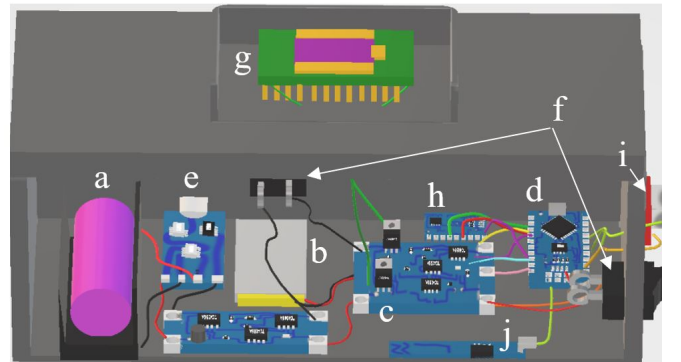


Fig. 1. Design and representation of the portable and wireless signal transducer. The system is composed of: (a) the Lithium ion battery, (b) the lithium polymer battery, (c) the main circuitry of the apparatus, (d) the microcontroller module, (e) the module with a female micro-usb port, (f) the switches, (g) the graphene sensing surface, (h) the ADC, (i) the temperature and humidity sensor, (j) the bluetooth module.

While the circuitry is contained within the enclosure, the sensing surface (*g*) is mounted on the outside to have direct exposure to the environment. Using an operational amplifier (op-amp), the main circuitry provides an analog signal inversely proportional to the resistance of the graphene sensor. A 16-bit digital converter (ADC) ADS1115 (*h*) is used to relay this signal to the microcontroller; which is a low-cost Arduino compatible ATmega328P with low power consumption. A temperature/humidity sensor AM2302 (*i*) and a HC-05 Bluetooth module (*j*) are also attached to the microcontroller's module. The AM2302 sensor is particularly relevant for graphene-based detectors since temperature and humidity can change their response. Therefore, recording the fluctuations in ambient conditions is necessary. The Bluetooth module enables a wireless connection with any cellphone to display the data through a mobile application.

The type of graphene chemiresistor used in this work is presented in Fig. 2a as a schematic and as a picture of the actual device mounted on a PCB sample holder. The graphene film, grown by chemical vapor deposition on copper foil, is purchased from a commercial supplier (Graphenea). The graphene samples are transferred onto cleaved Si/SiO<sub>2</sub> wafers by the use of a standard procedure involving PMMA coating and copper etching [5]. Finally, Ti/Au contacts were patterned onto the device using a shadow mask and a metal evaporator.

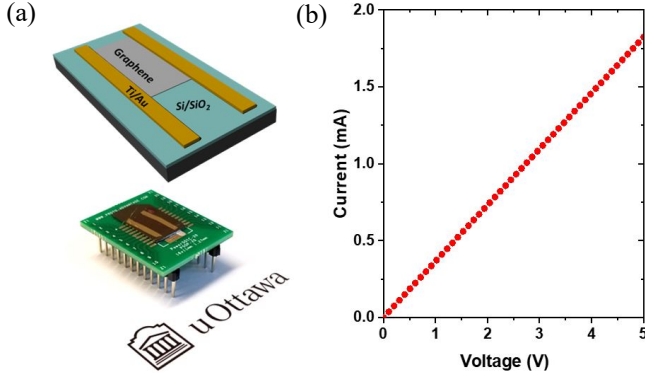


Fig. 2 (a) Schematic and picture of the graphene sensors used in this study. (b) Current-voltage characteristic of a graphene sensor with  $R_s = 2741 \Omega$ .

### III. CIRCUIT DESIGN AND IMPLEMENTATION

The main circuitry of the device uses the concepts of an inverting op-amp presented in Fig. 3. The op-amp converts the current-source provided by the sensor's resistance to a voltage signal, which can then be analyzed by the microcontroller. By choosing the feedback resistance ( $R_f$ ) and the input voltage ( $V_{in}$ ), the value of the resistance ( $R_s$ ), corresponding to our graphene-based sensor, can be accurately calculated using the measured output voltage ( $V_{out}$ ).

$$R_s = \frac{-V_{in}}{V_{out} - V_0} \cdot R_g \quad (1)$$

This relation is demonstrated in (1) [6] where  $V_0$  is the reference voltage of the main circuit [7]. Since the average resistance of the sensor is typically measured to be around  $2500 \Omega$ , we can optimize the reading accuracy by selecting  $R_f$  and  $V_{in}$ . An input voltage  $V_{in} = 1.25 \text{ V}$  and a feedback resistance  $R_f = 2500 \Omega$  allows us to use the full dynamic range of the ADC spanning from  $\pm 4.096 \text{ V}$ .

A typical example of the current-voltage characteristic of a graphene sensor is presented in Fig. 2b, where the resistance of the particular sensor was  $R_s = 2741 \Omega$ . Note that  $V_0$  is also monitored to accurately measure the gain of the op-amp.

The output voltages are transmitted to the 16-bit ADC to provide digital readings to the microcontroller. The 16 bit allows a resolution of  $0.125 \text{ mV/bit}$  from  $-4.096$  to  $4.096 \text{ V}$ . The values for  $R_f$  and  $V_{in}$  determine the minimum and maximum measurable resistances, which, in our experiment, correspond to  $763 \Omega$  and  $24.7 \text{ M}\Omega$ , respectively. Equation 2 shows the relation between the resolution,  $r_z$ , in Ohm per bit of data, and the squared value of  $R_s$  in Ohm:

$$r_z = 4 \times 10^{-8} R_s^2 \quad (2)$$

where coefficient  $4 \times 10^{-8}$  in (2) is in units of  $\Omega^{-1} \cdot \text{bit}^{-1}$  and is calculated from the ADC's resolution and the derivative of (1). The results of (2) is shown in Fig. 3b with the upper and the lower limits indicated by "A" and "B". Note that the resolution  $r_z$ , as defined in the units of  $\Omega/\text{bit}$ , depends on the square of the measured resistance  $R_s$ .

The uncertainty of the measurements of  $R_s$  strongly depends on the uncertainty of the regulated voltage source ( $V_{in}$ ), the feedback resistor ( $R_f$ ), and the output voltage ( $V_{out}$ ). Since the uncertainty of  $V_{out}$  is negligible compared to the uncertainty of the  $V_{in}$  and  $R_f$ , the uncertainty of the resistance can be calculated using (3).

$$\frac{\Delta R_s}{R_s} \approx \sqrt{\left(\frac{\Delta R_f}{R_f}\right)^2 + \left(\frac{\Delta V_{in}}{V_{in}}\right)^2} \quad (3)$$

The uncertainties of the feedback resistance, the sensor resistance and the input voltage are  $\Delta R_f$ ,  $\Delta R_s$  and  $\Delta V_{in}$  respectively, in (3). Using actual values of  $2505 \Omega$ ,  $1 \Omega$ ,  $1247.0 \text{ mV}$  and  $0.5 \text{ mV}$  for  $R_f$ ,  $\Delta R_f$ ,  $V_{in}$  and  $\Delta V_{in}$ , the uncertainty on the sensor's resistance is found to be  $0.06\%$ .

(a) (b)

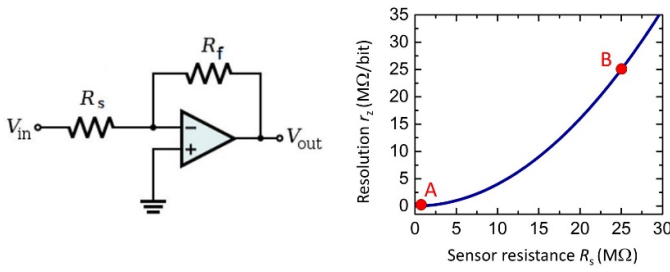


Fig. 3 (a) Diagram of an inverting operational amplifier. (b) Graphical representation of the resolution of our circuit as a function of the sensor resistance (based on (2)). For our circuit, the accessible range is contained between the points “A” and “B”.

To summarize, the circuit is optimized for accuracy and resolution in the range where our sensor is expected to operate (0.8 to 250 k $\Omega$ ). This range was determined by the particular sensors tested in our experiment. However, the circuit can be adapted for different types of 2D material sensors by simply modifying the input voltage and the feedback resistance accordingly.

#### IV. MOBILE APP AND CONNECTIVITY

##### A. Microcontroller and the code

Using its many analog and digital inputs, the micro controller, programmed with Arduino in C coding language, interprets the data from the temperature and humidity sensor along with the information received from the ADC. The micro controller calculates the resistance of the sensor using (1) and the input from  $V_{in}$  and  $V_0$  from the ADC. Afterwards, the micro controller sends the data wirelessly via Bluetooth to the application.

##### B. Architecture of the application

The application, currently available on Android phones, utilizes the Bluetooth module to provide real time monitoring and recording of the sensor’s resistance to an application. After the connection with the Bluetooth module, the application periodically receives data from the microcontroller and plots the resistance over time for long term monitoring. Fig. 4 shows such a recording as actually displayed on a cell phone. Simultaneously, the temperature and humidity readings are collected from their respective sensor in numeric format. The application can save all data as a csv file on the cell phone’s internal flash memory so that it can be stored and analyzed using software beyond the mobile platform.

Remote connectivity of sensing devices (such as Bluetooth as demonstrated in this work) offers a broad range of advantages for applications in security, health and environmental monitoring.

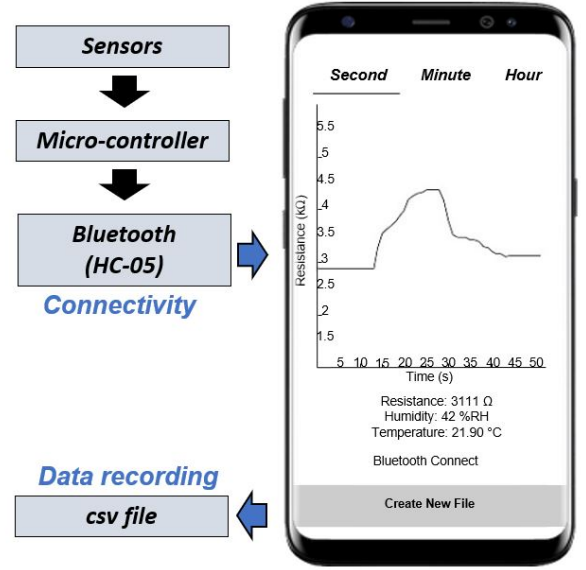


Fig. 4. A visual representation of the data’s path including a screenshot of the application’s interface.

#### V. RESULTS OF TESTS

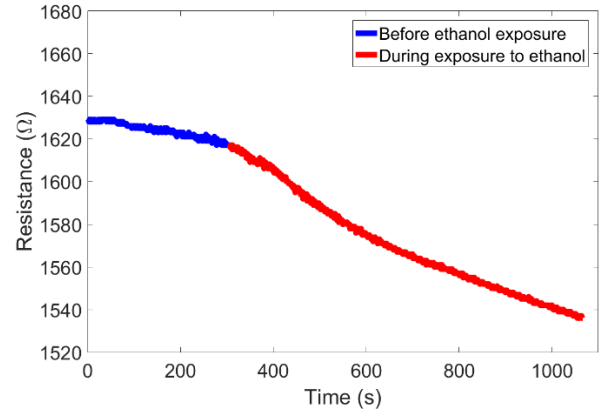


Fig. 5. Resistance ( $\Omega$ ) of the sensor over time (s) in the presence of ethanol, as recorded by the apparatus.

With the goal of using the apparatus to detect changes in the sensor’s resistance with exposure to ethanol, multiple tests were conducted. Fig. 5 shows the resistance as a function of time of a typical test where ethanol is evaporated in the vicinity of the sensor 300 s after the data collection has started. The ethanol triggers a dramatic change in the resistance slope. A relative change in resistance of 5% is monitored during a period of 700 s (~11 minutes) over which the sensor is exposed to traces amount of ethanol. This sensitivity is consistent with previous reports [8] and demonstrates the functionality of the device.

## VI. CONCLUSION

In conclusion, this paper presents a portable, hand-held, wireless signal transducer that can be adapted for different 2D materials sensors with the purpose of detecting environmental changes. With the goal of collecting sensing responses in the field, the apparatus utilized the advantage of Bluetooth, along with a cellphone interface, as a wireless solution for sending the sensing signal remotely to a user. As an example, we demonstrate that the device we developed provides accurate detection for a graphene sensor with typical resistance of a few kilo Ohm. As the field of 2D materials-based sensors is rapidly progressing we anticipate that our device provides a valuable resource in integrating the chemiresistor with existing environmental monitor platforms.

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