Evaluation of Environmental Enclosures for Effective Ambient Ozone Sensing in Wrist-worn Health and Exposure Trackers

Tahmid Latif, James Dieffenderfer, Akhilesh Tanneeru, Bongmook Lee, Veena Misra, and Alper Bozkurt
Department of Electrical and Computer Engineering, NC State University, Raleigh, NC 27606, USA
aybozkur@ncsu.edu

2021 IEEE Sensors | 978-1-7281-9501-8/21/$31.00 ©2021 IEEE | DOI: 10.1109/SENSORS47087.2021.9639530

***Abstract*—The ambient environmental conditions, most notably ozone concentration, play a critical role in exacerbating asthma related symptoms. Wearable devices offer a great potential for asthma care and management by tracking health and environmental status. Wearable devices in the form factor of a wristband using ultra-low power ozone sensors can provide a localized, real-time, and vigilant monitoring of users' ambient environment. This work presents a preliminary investigation of environmental enclosures for such a custom designed wrist-worn wearable device for asthma. Enclosure design plays an important role in ensuring optimal environmental and gas sensor operation. In this study, we studied openings along the sidewall of the wrist-worn device covered with commercially available expanded polytetrafluoroethylene-based membranes to provide the required air flow while ensuring resistance to water.**

Keywords—asthma; environmental sensing; ozone exposure; ozone sensor; wearables

I. Introduction

The advent of wearable devices have caused a quantum leap in portable health monitoring or tracking. While initially focusing on fitness or exercise tracking, wearable devices now can monitor important physiologic parameters for health management [1], [2]. Asthma is one of the most prevalent health conditions where wearable devices can help manage the symptoms through correlated sensing of changes in physiologic and ambient environmental parameters to predict the onset of an asthma exacerbation [3], [4]. While current wearable asthma sensing mostly focuses on respiration, coughing or wheezing monitoring, or digital-diary-recording of the symptoms, many of these require the active engagement of the user [5]–[7]. There is a need for more efficient personal environmental monitors targeted towards vigilant asthma monitoring.

Ozone is a lung irritant and considered to be a common trigger for asthma exacerbation. Exposure to ozone at levels even below the US National Ambient Air Quality Standards (NAAQS) limits, i.e. 70 parts per billion (ppb), can aggravate respiratory symptoms in asthmatic patients [8], [9]. An increasing number of asthmatics and resulting healthcare expenditure in the US and worldwide [10], [11] call for improved asthma care and management. At the National Science Foundation Nanosystems Engineering Research Center for Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST), we work towards developing wearable engineered systems for real-time, vigilant monitoring for health application [3], [4]. For the asthma application, we use multi-modal wearable sensors – such as ozone, photoplethysmography (PPG), motion, temperature, relative humidity – for correlated sensing of physiologic and micro-environmental parameters. In these, ultra-low power ozone [12], [13], ambient temperature, and relative humidity sensors collect localized data with higher spatial and temporal resolutions in comparison to averaged data available online from weather stations. With advanced data analytics, we work on predicting the asthma exacerbation to enable actionable decision making.

Collecting reliable data using these environmental sensors faces a trade-off between environmental ruggedness and sensor function. A completely enclosed device would provide the highest resilience to environmental challenges such as water penetration, but also block the air flow and venting. This would lead to an unreliable or incorrect data collection with reduced sensitivity. Vent holes opened along the sidewall of the wrist-worn device can allow an almost uninterrupted airflow to the environmental sensors for improving ozone and temperature sensing while also letting water or dust in. For this study, we have installed specialized protective membranes (pressure-vents) on such openings. These expanded polytetrafluoroethylene (ePTFE)-based membranes are commercially available and improve air flow while providing protection from water or dust. This paper assesses the ambient ozone sensing capability of sensors placed within enclosures hosting such protective membranes.

In the following sections of the paper, we have discussed the procedure for a custom, low-power, wearable ozone sensor fabrication, its integration within our wrist-worn device, the manufacturing of environmental enclosures, and the testing setup with the wearable device system under ozone exposure. This is followed by analysis and discussion of the ozone sensor testing data for various enclosure types.

II. Materials and Methods

A. Sensor Fabrication and Device Integration

The sensor fabrication began with oxidation of silicon wafers for electrical isolation from the substrate. The silicon wafers were cleaned in a JTB-100 solution to remove any surface contaminants. A 3000 Å field oxide was then grown by wet oxidation for 30 minutes at 1000°C in an $O_2/H_2/HCl/N_2$ environment. After oxidation, the 100 Å of metal oxide sensing layer SnO_2 was deposited in an Atomic Layer Deposition (ALD) reactor (Cambridge Nanotech

This work was supported by the National Science Foundation through awards IIS-2037328, IIS-1915599, and EEC-1160483 (ERC for ASSIST).

Savannah 100 model) via alternating exposures to the precursor, Tetrakis(dimethylamino)tin (TDMASn) and ozone reactant at 200°C. The metal oxide films were then annealed in a Lindberg furnace with an air ambient at 600°C for 2 hours to ensure the desired crystalline phase. Finally, square electrical contacts were deposited via electron-beam evaporation in a high vacuum (10^{-6} Torr) with a shadow mask. The contacts consisted of a 100 Å titanium adhesion layer followed by 2500 Å of gold. ALD SnO_2 film thickness was verified by Scanning Tunneling Electron Microscopy (STEM) and the crystalline phase was confirmed by the grazing angle X-Ray diffraction (GA-XRD) patterns [13].

Each of the wafers was diced into 1×1 cm^2 dies each containing four sensors and attached to the center of a custom printed circuit board (PCB) using double-sided tapes, with the contacts wire bonded to designated pads. These ozone sensor daughterboards were connected to a custom wearable data acquisition system [3] using connection headers. The SnO_2 ozone sensors were n-type semiconductors, so their baseline resistance increased when exposed to ozone gas molecules. The sensors faced downward on an Ultraviolet (UV) LED on the PCB. This UV LED (operating at a 10% duty cycle) was responsible for desorbing the oxidizing gas molecules when switched on and recovering the sensor resistance to an initial baseline value [12].

B. Environmental Enclosure Design

The initial ozone testing was performed in a completely open wrist-worn ozone sensor system without any enclosure. Then, this was placed in a completely closed enclosure with no openings. With all sensors inside a closed package, sensor output was expected to be lower. As an intermediate step, we introduced 3.5 mm circular openings along the sidewall of the enclosure. These openings were hypothesized to passively allow some air flow to the sensor inside. In this preliminary study, we positioned two and six openings along the sidewall (Fig. 1). While the two hole provided a "single" path for air flow away from most of the device electronic components, the six hole design had maximal openings to minimize hindrance of air flow without compromising the structural integrity of the enclosure. These enclosure prototypes were manufactured using stereolithography (SLA) 3D printing. SLA-printed structures are generally non-porous and not water-permeable, making them suitable for our testing.

As the next step, we added ePTFE-based protective membranes (Fig. 1) over the openings to allow air flow while providing water-resistance, thereby protecting internal device components. These commercially available membranes, called "pressure-vents," are designed to improve air flow and minimize pressure differential between the inside and outside of the device enclosure (PE130306, W. L. Gore & Associates, Inc., Newark, DE, USA).

C. Sensor Testing

The sensors and enclosures were tested in a custom stainless steel chamber with a NIST-certified Teledyne T700U gas calibrator to deliver precise ozone concentrations. In order to simulate dry ambient conditions, zero air (RH=0%) was used as the carrier gas. Zero air was obtained from AirGas (AI-Z300) and composed of N_2 and O_2 with an O_2 ratio between 0.195-0.235. The total hydrocarbon contamination is less than 0.1 ppm. Ozone is generated from zero air using an arc lamp and diluted with the carrier gas to achieve parts per billion (ppb) accuracy. A total flow rate was chosen as 3 SLM, allowing the Teledyne unit to achieve the desired ozone concentrations in parts per billion (ppb).

In this case, the ozone sensors were connected to a wrist-worn data acquisition system (Fig. 1) and tested in the testing chamber at 50, 100, and 150 ppb. Ozone gas at each concentration level flowed through the chamber in multiple short bursts, each lasting approximately two minutes for testing the reliability and repeatability of the sensor response. The wrist-worn ozone sensor system without any enclosures, with no opening (closed), two-opening, six-opening, and six-opening covered with six pressure-vent membranes were tested in this setup. A custom-built iOS app was developed for data aggregation through the wrist-worn ozone sensor system. The app used Bluetooth Low Energy (BLE) protocol in order to collect the device data – ozone sensor resistance, temperature, and relative humidity – at a sampling rate of 20 Hz and to control the UV LED for sensor recovery.

III. Results and Discussion

The collected data (Fig. 2) were analyzed in MATLAB (MathWorks Inc, Natick, MA, USA). For each of the test scenarios, the data was filtered before computing the derivative of the sensor resistance with respect to time (dR/dt) (Fig. 3). dR/dt would give a measure of ozone concentration and can be correlated with actual/ambient ozone level concentration [14].

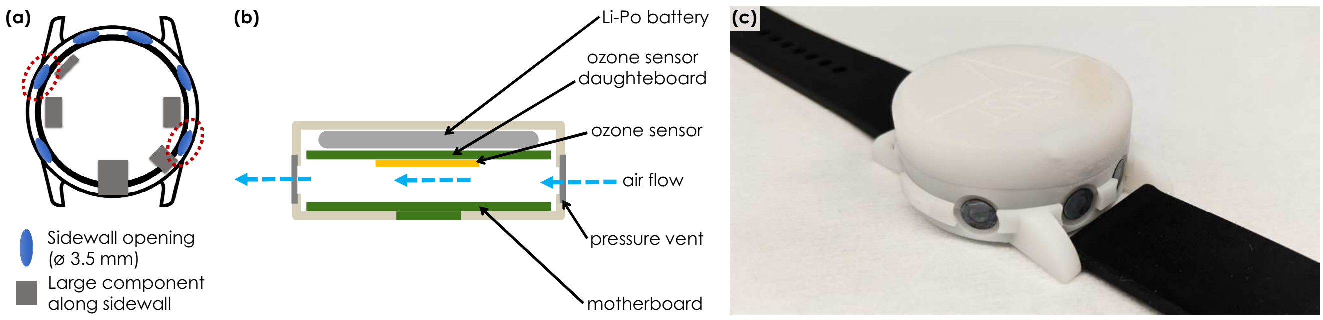

Fig. 1. (a) Illustration of the ASSIST wrist-worn device showing locations of openings along the sidewall of the enclosure. These location were selected based on their relative lack of proximity from electronic components inside the enclosure. The pressure-vents were attached on these openings for the six-opening enclosure. Vent holes in the two-opening enclosure are circled in red. (b) Illustration showing the placement and position of the ozone sensors on a PCB inside the wearable. (c) Image of the wrist-worn device with an SLA 3D printed enclosure, shown here equipped with pressure-vents.

A slight difference in peak values of dR/dt were observed when the same ozone level concentrations were applied to the system. While standard deviation between these peaks were not very high (typically less than 40 Ω/min) the difference can be attributed to potential variation of pressure of the carrier gas in the testing setup.

The representative data for a single ozone sensor for each enclosure type is presented in Fig. 2 and Fig. 3. Variations between output levels were observed between the different enclosure designs (Fig. 4). Less holes therefore less air flow with the ambient environment meant lesser ionosorption of ozone gas molecules, thereby resulting in a lower dR/dt. Difference between data points at 0 ppb was much lower than that at other concentration levels. Data at each concentration level was averaged over five consecutive peaks, and plotted against ozone concentration (Fig. 4). "No enclosure" case had the highest values and "completely closed enclosure" the lowest as expected. Data for the six-opening enclosure was the closest to the no enclosure scenario. These values decreased slightly when the pressure-vents covered the holes. It was noteworthy that the slope for the data with pressure-vents was very similar to that with no enclosure. This could mean a similar sensitivity performance which needs to be further tested using multiple enclosures and sensors, to be performed as the next stage of this research study. Data from a wider range of ozone levels also need to be collected.

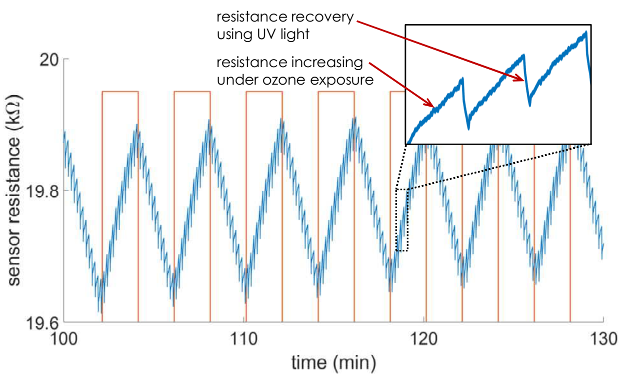

Fig. 2. Representative data showing sensor response – resistance as a function of time – when exposed to two-minute bursts of ozone at 100 ppb. Overall sensor resistance increased in presence of ozone and went down in its absence. Inset image shows resistance increasing and how an UV LED operating at 10% duty cycle attempted to recover the sensor resistance such that it returned to an initial baseline value at the end of a run.

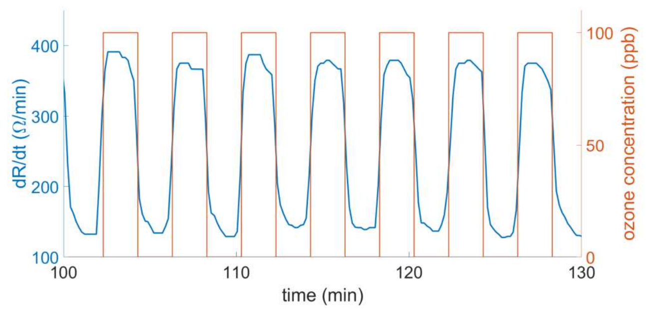

Fig. 3. Representative data showing dR/dt – the derivative of the sensor resistance as a function of time – for an ozone sensor exposed to 100 ppb. This data can be correlated with actual ozone concentration levels (shown on the vertical axis to the right).

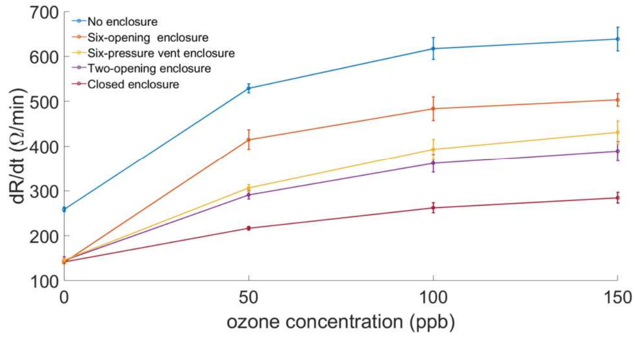

Fig. 4. Plot of dR/dt – the derivative of the sensor resistance as a function of time – of a sensor vs ozone concentration levels for five different enclosure scenarios. The "no enclosure" data had the highest reading while the "closed enclosure" data the lowest.

IV. Conclusion

We have evaluated various enclosure strategies on benchtop and in vitro for a wrist-worn ozone sensor designed for asthma management. A water- and dust-resilient enclosure, required for a rugged and robust wearable sensing performance, significantly reduced the sensitivity with respect to having no enclosure at all. Introduction of pressure-vent covered holes on the sidewalls of the enclosure improved the sensitivity as expected while providing water- and dust-resistance. Opening more holes improved the reduction caused by the pressure-vents covering the holes. Our results suggest that the enclosure with six pressure-vents performed reasonably well with a sensitivity close to that of no enclosure. The next stages of this research includes performing similar tests with these enclosures and a higher number of ozone sensors . This is expected to greatly assist our research team in adapting wrist-worn ozone sensor systems for testing and deployment under real-world conditions.

Acknowledgment

The authors thank Yilu Zhou and Dr. Steven Lipa for help with wire bonding of the sensors. This work was performed in part at the NC State University Nanofabrication Facility (NNF), a member of the North Carolina Research Triangle Nanotechnology Network (RTNN), which is supported by the National Science Foundation (Grant ECCS-1542015) as part of the National Nanotechnology Coordinated Infrastructure (NNCI).

References

[1] J. Greiwe and S. M. Nyenhuis, "Wearable technology and how this can be implemented into clinical practice," *Curr. Allergy Asthma Rep.*, vol. 20, no. 8, 2020, doi: 10.1007/s11882-020-00927-3.

[2] J. M. Raja *et al.*, "Apple watch, wearables, and heart rhythm: where do we stand?," *Ann. Transl. Med.*, vol. 7, no. 17, pp. 417–417, 2019, doi: 10.21037/atm.2019.06.79.

[3] J. Dieffenderfer *et al.*, "Low-power wearable systems for continuous monitoring of environment and health for chronic respiratory disease," *IEEE J. Biomed. Heal. Informatics*, vol. 20, no. 5, pp. 1251–1264, 2016, doi: 10.1109/JBHI.2016.2573286.

[4] V. Misra *et al.*, "Flexible technologies for self-powered wearable health and environmental sensing," *Proc. IEEE*, vol. 103, no. 4, pp. 665–681, 2015, doi: 10.1109/JPROC.2015.2412493.

[5] R. Venkataramanan *et al.*, "Determination of personalized asthma triggers from multimodal sensing and a mobile app: Observational study," *JMIR Pediatr. Parent.*, vol. 2, no. 1, pp. 1–12, 2019, doi: 10.2196/14300.

[6] J. Zhang, W. Ser, J. Yu, and T. T. Zhang, "A novel wheeze detection method for wearable monitoring systems," *2009 Int. Symp. Intell. Ubiquitous Comput. Educ. IUCE 2009*, vol. 639798, pp. 331–334, 2009, doi: 10.1109/IUCE.2009.66.

[7] U. Katwa and E. Rivera, "Asthma management in the era of smart-medicine: devices, gadgets, apps and telemedicine," *Indian J. Pediatr.*, vol. 85, no. 9, pp. 757–762, 2018, doi: 10.1007/s12098-018-2611-6.

[8] A. J. Burbank, A. K. Sood, M. J. Kesic, D. B. Peden, and M. L. Hernandez, "Environmental determinants of allergy and asthma in early life," *J. Allergy Clin. Immunol.*, vol. 140, no. 1, pp. 1–12, 2017, doi: 10.1016/j.jaci.2017.05.010.

[9] M. L. Hernandez *et al.*, "Low-level ozone has both respiratory & systemic effects in African-American adolescents with asthma despite asthma controller therapy," *J. Allergy Clin. Immunol.*, vol. 142, no. 6, pp. 1974–1977, 2018, doi: 10.1016/j.jaci.2018.08.003.Low-level.

[10] Centers for Disease Control and Prevention. (accessed: 06.30.2021) "Most recent national asthma data." https://www.cdc.gov/asthma/most_recent_national_asthma_data.htm.

[11] T. Nurmagambetov, R. Kuwahara, and P. Garbe, "The economic burden of asthma in the United States, 2008-2013," *Ann. Am. Thorac. Soc.*, vol. 15, no. 3, pp. 348–356, 2018, doi: 10.1513/AnnalsATS.201703-259OC.

[12] S. Mills, B. Lee, and V. Misra, "Room temperature ozone and humidity response evolution of atomic layer deposited SnO_2 sensors," *Proc. IEEE Sensors*, vol. 2017-Decem, pp. 1–3, 2017, doi: 10.1109/ICSENS.2017.8234334.

[13] S. Mills, M. Lim, B. Lee, and V. Misra, " Atomic layer deposition of SnO_2 for delective room temperature low ppb level O_3 sensing," *ECS J. Solid State Sci. Technol.*, vol. 4, no. 10, pp. S3059–S3061, 2015, doi: 10.1149/2.0111510jss.

[14] C. H. Wu *et al.*, "Fast gas concentration sensing by analyzing the rate of resistance change," *Sensors Actuators, B Chem.*, vol. 209, pp. 906–910, 2015, doi: 10.1016/j.snb.2014.12.066.