CMOS-BASED LUMINESCENT CO_2 SENSOR

M. Ratterman,[1] L. Shen,[1] D. Klotzkin,[2] A. Bhattacharya, [3]and I. Papautsky[1*]

[1]School of Electronic and Computing Systems, University of Cincinnati, Cincinnati, OH USA

[2]Department of Electrical and Computer Engineering, Binghamton University, Binghamton, NY USA

[3]College of Medicine, University of Cincinnati, Cincinnati, OH USA

ABSTRACT

In this work, we demonstrate a portable optical CO_2 sensor using CMOS image sensing with polarization signal isolation. Luminescent CO_2 detection methods generally exhibit faster response time and increased sensitivity over the established commercial sensors (NDIR, electrochemical), but require bulky and expensive spectrophotometry equipment which confines them to a lab. Components used in our CMOS-based luminescence system can typically be found in most consumer cellphones, making it an economical alternative for field use [1,2].

KEYWORDS: CMOS image sensor, Gas sensor, CO2 sensor

INTRODUCTION

Abnormal levels of carbon dioxide (CO_2) can have adverse health effects, yet prolonged exposure to high levels of CO_2 (>2%) have been reported in various occupational setting such as firefighting and mining. Such levels can result in adverse respiratory effects as well as inhibition of cell functions even in healthy adults [4-5]. CO_2 detectors using the NDIR (Non-Dispersive Infrared) principle have been demonstrated. While this method displays good sensitivity, it often requires expensive, bulky equipment which deters its implementation in occupational settings. These sensors also display increased response times of greater than 15 sec per measurement. Electrochemical methods have been demonstrated as a low-cost alternative, but they degrade over time [6].

Current, research in Lab-on-a-Chip (LOC) and microfluidic applications has focused on the miniaturization of components to increase throughput, decrease reagents, decrease sample size, and increase sensitivity. Many of these analyses focus on optical methods requiring large and bulky spectroscopic equipment, which limits them in Point-of-Care (POC) use. Recently, we have demonstrated a portable oxygen (O_2) sensor using a CMOS image array. The developed sensor is based on the luminescent quenching of platinum octaethlyphorphine (PtOEP) and cross polarization of the excitation source. To increase optical stability, we incorporated Rhodamine B as a reference dye [2]. This stacked method is commonly used in microfluidic sensors to reduce size while maintaining sensor sensitivity. To extend this approach to detection of CO_2, a new luminescent film which exhibits concentration-dependent emission in the visible range was necessary. In this work, we use hydroxypyrene trisulfonic (HPTS) acid as CO_2 indicator, in a stacked arrangement (Fig. 1a). As CO_2 concentration increases, luminescent quenching of the HPTS film leads to decreased emission intensity, which was measured by the CMOS array.

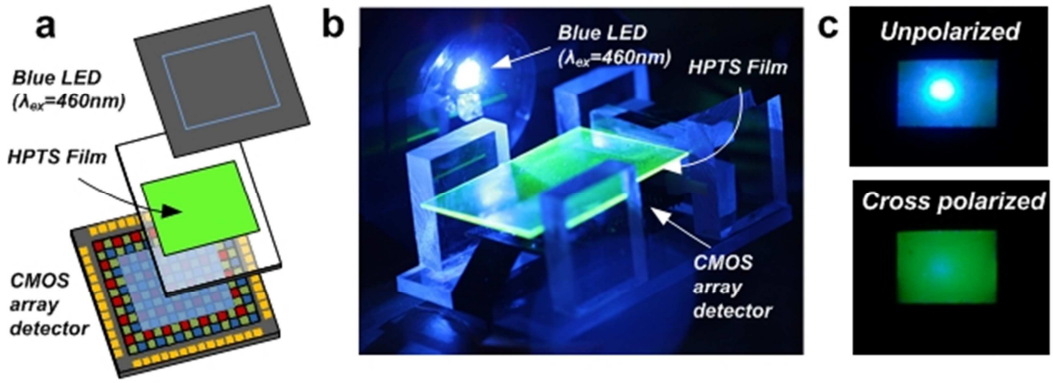

***Fig. 1**: (a) Stacked arrangement of CO_2 detector showing light source (blue LED), CO_2 sensitive HPTS film, and CMOS array detector. Cross-polarization scheme is not shown.(b) Picture showing sensor setup at 0% CO_2 (c) Cross polarization filtering out excitation source to show fluorescein emission*

METHODS

We demonstrated CO_2 detection by encapsulating hydroxypyrene trisulfonic (HPTS) acid in ethyl cellulose. HPTS has an emission peak ~520 nm, with excitation peaks in the visible blue (λ_{exc}=460nm) and UV (λ_{exc}=380nm) range. This material exhibits fluorescence quenching in the presence of CO_2 [3]. A blue LED (R20BLU-F-0160) (λ_{exc}=460nm) was used for excitation, while a CMOS detector (OmniVision, OV9810) was used to detect emission in the green channel (Fig.1*a*). The sensor has a packaged footprint of 8.195 mm x 7.535 mm, with 6.160 mm x 4.606 mm imaging area. The active array size was 3488 x 2616 pixels (9 megapixel resolution), each approximately 1.75 µm x 1.75 µm. The cross-polarization signal isolation was used to filter out excitation light from the LED and increase sensitivity of the CMOS array (Fig.1*c*).

RESULTS AND DISCUSSION

We first characterized the HTPS films, and found them to age. For this, film emission was monitored at room temperature over a 4 week period using a spectrophotometer (Cary Eclipse) to quantify emission peak intensity under excitation at 380nm and 460nm (Fig. 2). A dramatic reduction (10x) in emission at 520nm was measured, indicating that films must be used immediately after preparation.

By taking advantage of the channel selectivity of the CMOS detector, and filtering out excitation light using cross-polarization, we were able to fully characterize and calibrate the sensor (Fig.3). The CMOS detector's color discriminating capability is not sufficient by itself to adequately detect HPTS emission. Since we are using a novel stacked arrangement for our sensor setup, the blue LED with a central emission wavelength of 460nm will saturate the CMOS array resulting in high noise, thereby reducing sensitivity. Optical signal isolation based on cross-polarization has been proven to be a simple approach to filter out excitation light regardless of wavelength [1].

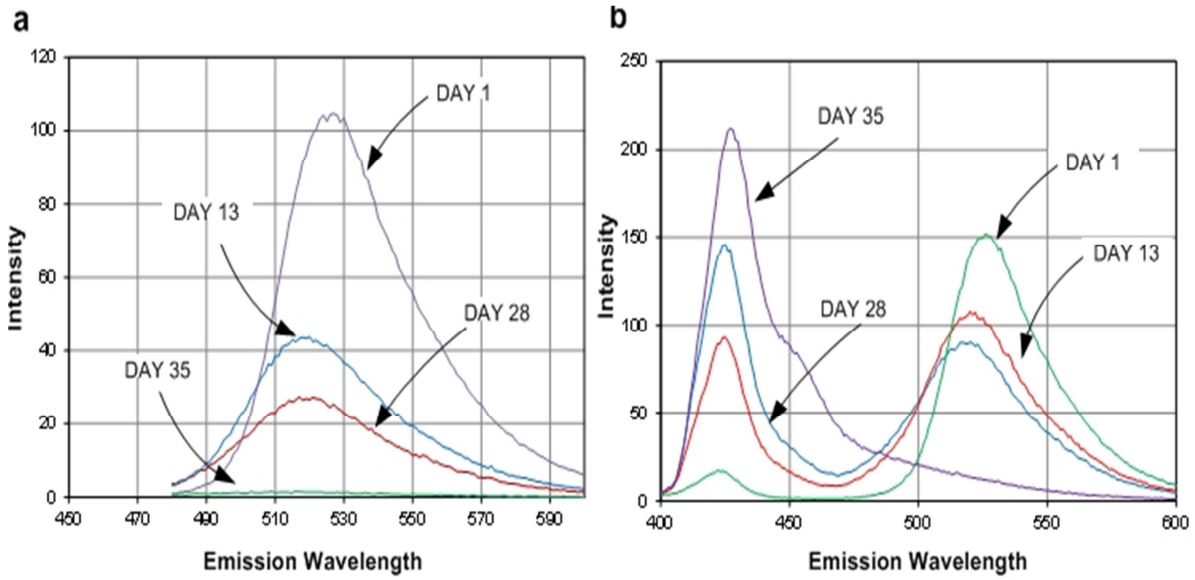

Fig. 2: *Spectrophotometry measurements of HPTS film over time. (a) Emission spectra under 380nm excitation and (b) under 460nm excitation taken over a 4 week period*

To obtain the emission intensity from the film only, background emission from underlying glass substrate was subtracted from the signal measurements and intensity in the green channel was monitored from 0-5% CO_2. A Stern-Volmer (SV) relationship was constructed by normalizing the intensity to the initial value at 0% CO_2 (Fig.4). The slope of the SV line yields sensitivity of the sensor which is comparable to previously demonstrated luminescent CO_2 detection methods. To verify feasibility for field use, effects of humidity and O_2 interference were investigated. Humidity was varied 0-70% inside the test chamber. The sensor response was independent of humidity, and had a standard deviation of only 1% in all channels. The O_2 concentration was varied from 0-100% inside the test chamber, resulting in a <1% signal deviation in all channels. The sensor showed a fast response time of <2s, which is much faster than the typical 20s of commercial sensors.

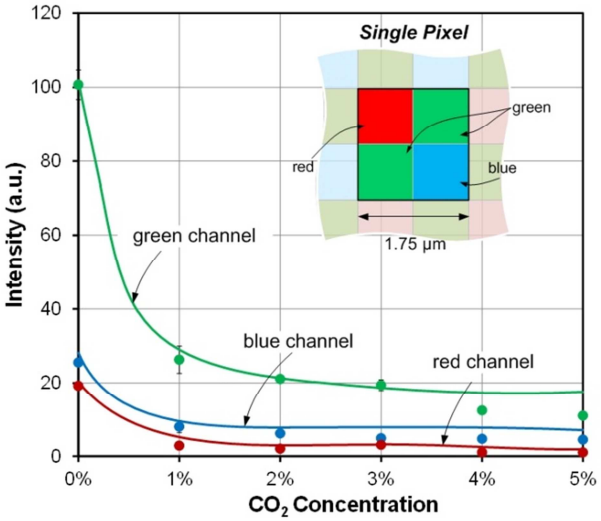

Fig. 3: *HPTS emission intensity in RGB channels vs. CO_2 concentration*

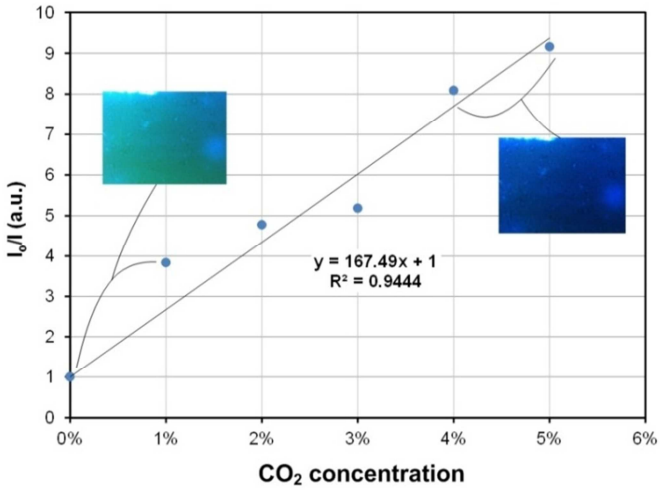

Fig. 4: *Stern-Volmer plot of the CO_2 sensor from 0-5% concentration*

CONCLUSION

A prototype CO_2 sensor using CMOS-based luminescence detection was successfully demonstrated. The CO_2 sensor is highly sensitive in the 0-5% CO_2 range, is immune to interference by humidity and O_2, and exhibits fast response times. Taking advantage of the spatial resolution of the CMOS array, it may be integrated with other luminescent sensors (e.g., O_2 or CO). Ultimately, this simple CO_2 sensor can be integrated into lab-on-a-chip devices for point-of-care sensing applications.

ACKNOWLEDGEMENTS

This work was supported by the grant from the National Science Foundation (ECCS-0930305) and the National Institute of Occupational Safety and Health (NIOSH) Pilot Research Project Training Program at the University of Cincinnati (T42OH008432).

REFERENCES

[1] Banerjee, A., Pais, A., Papautsky, I., & Klotzkin, D. “A polarization isolation method for high-sensitivity, low-cost on-chip fluorescence detection for microfluidic lab-on-a-chip,” IEEE Sensors Journal, vol. 8, 621-627, 2008.

[2] Shen, L., M. Ratterman, D. Klotzkin and I. Papautsky, "A CMOS optical detection system for point-of-use luminescent oxygen sensing," Sens. Actuators B, vol. 155, pp. 430-435, 2011.

[3] Chu, C., Lo, Y. “Highly sensitive and linear optical fiber carbon dioxide sensor based on sol-gel matrix doped with silica particles and HPTS,” Sensors and Actuators, B: Chemical, vol. 143, 205-210, 2009.

[4] Caretti, D., Coyne, K. M. “Unmanned assessment of respirator carbon dioxide levels: Comparison of methods of measurement,” Journal of Occupational and Environmental Hygiene, vol. 5, 305-312, 2008.

[5] Robertson, D. S. “The rise in the atmospheric concentration of carbon dioxide and the effects on human health,” Medical Hypotheses, vol. 56, 513-518, 2001.

[6] Dansby-Sparks, R. N., Jin, J., Mechery, S. J., Sampathkumaran, U., Owen, T. W., Yu, B. D., et al. “Fluorescent-dye-doped sol-gel sensor for highly sensitive carbon dioxide gas detection below atmospheric concentrations. Analytical Chemistry, vol. 82, 593-600, 2010.

CONTACT

*Ian Papautsky, tel: +1-513-556-2347, ian.papautsky@uc.edu