Detection of CO2 gas using NDIR gas sensor

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2 DECLARATION

I hereby declare that the project report entitled "Detection of CO_2 gas using NDIR gas sensor" submitted by me in partial fulfillment of the requirement for the internship certificate from CSIR-Central Electronics Engineering Research Institute is authentic work undertaken by me.

I also confirm that this report is only prepared for my academic requirement not for any other purpose.

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CERTIFICATE

This is to certify that the dissertation entitled "Detection of CO_2 gas using NDIR gas sensor" submitted by RISHAV PANDEY to the Department of Electronics and Tele-Communication Engineering, Jabalpur Engineering College, Jabalpur-482011 is a bonafide record of the research work carried out by him under my supervision and guidance to the best of my knowledge. The content of the thesis full or parts have not been submitted to other institute or university for the award of any other degree or diploma to the best of my knowledge.

भवदीय/Yours,

Vijay Chatterjee

नाम/Name (डॉ. विजय चटर्जी/Dr. Vijay Chatterjee)
पदनाम/Designation: वरिष्ठ वैज्ञानिक/Sr. Scientist

Abstract

NDIR is an industry term for "non-dispersive infrared" and is the most common type of sensor used to measure carbon dioxide, or CO2. However, this gas detector is not limited only for CO2 gas but can be used to detect any IR- Active gas like CO, NO, SO2 but at different wavelengths of Infrared Radiation. It is called as Non-Dispersive because the IR light which passes through the gas chamber is not pre-filtered. In NDIR Gas Sensors, generally two main things happen:
1. Beer-Lambert Law
2. IR-Spectroscopy

Since, the Infrared Radiation passes through a cylindrical gas chamber, its intensity varies exponentially as the length of the chamber and the concentration of CO2 increases. Thus, showing an application of Beer-Lambert Law. We can also see an interaction of IR light with the CO2 gas molecules, so we can say there is an involvement of IR-Spectroscopy in this project. NDIR gas sensor consists of an infrared source, detector, optical filter, gas cell, and electronics for signal processing. A single light source, dual wavelength type gas sensor has two detectors and two optical filters of different wavelengths which are placed in front of each detector. Before passing the CO2 gas we see the decrease in intensity of IR radiation (in the absence of IR active gas). This decrease in radiation is because of the length of the gas cell. Now, we pass CO2 gas through the inlet and simultaneously we pass the IR light, in this case the intensity of IR light decreases further because of the interaction of CO2 gas molecules with the same. It may be noted that the Infrared Radiation of wavelength ranging from 0.7 μm to 1 mm is passed through the gas cell. However, the CO2 gas molecules interact at a wavelength of around 4.26 μm causing vibration of the gas molecules. Some, of the infrared light is absorbed by the target gas while some IR radiation passes without any absorption. One that is absorbed by a target gas passes through the active filter with a particular bandwidth for the detection of the target gas while the other which does not interact with the target gas passes through the reference filter. NDIR gas sensor detects the decrease in transmitted infrared light which is in proportion to gas concentration. The difference between transmitted light intensities in these two bandwidths is converted into gas concentration. In this way, we can calculate the concentration of CO2 gas present in a gas chamber. While there are multiple methods, through which a target gas can be detected by an NDIR gas sensor like using Photodetectors

such as Photoconductivity Cell or using Thermal Detectors such as Pyroelectric detectors, Thermopile, Thermistor, Bolometer and Golay Cell. However, in this project we are limited only to pyroelectric detector for the detection of target gas. This project finds multiple applications in industries as well as in normal households. It can also be used to track the concentration of CO2 gas in a room present with NDIR gas sensor. As according to the World Health Organization, increased level of CO2 gas in environment can increase the risk of transmission of SARS-CoV-2 virus. In any given indoor environment, when CO2 level doubles, the risk of transmission also roughly doubles. The same has been confirmed by the researchers of Cooperative Institute for Research in Environmental Sciences (CIRES) and the University of Colorado Boulder. So, monitoring the level of CO2 gas in a room through this project can be an inexpensive and wonderful way to prevent the transmission of Covid-19 virus.

3 INTRODUCTION

A nondispersive infrared sensor (also known as an NDIR sensor) is a basic spectroscopic sensor that is frequently employed as a gas detector. It is non-dispersive because no dispersive device (such as a prism or diffraction grating) is employed to split the broadband light into a narrow spectrum suited for gas sensing (as is common in other spectrometers). A broadband light source and an optical filter are used in the majority of NDIR sensors to choose a narrow band spectral area that overlaps the absorption region of the gas of interest. In this case, a 50-300nm bandwidth may be considered narrow. Microelectromechanical systems (MEMs) or mid-IR LED sources may be used in modern NDIR sensors, which can be used with or without an optical filter. An infrared (IR) source (lamp), a sample chamber or light tube, a light filter, and an infrared detector are the primary components of an NDIR sensor. The IR light passes through the sample chamber and is directed towards the detector. In a separate chamber, a reference gas, usually nitrogen, is enclosed. According to the Beer–Lambert equation, the gas in the sample chamber absorbs particular wavelengths, and the detector measures the attenuation of these wavelengths to estimate the gas concentration. In front of the detector is an optical filter that filters out all light except that which the chosen gas molecules can absorb. Other gas molecules should ideally not absorb light at this wavelength and hence have no effect on the amount of light reaching the detector, although cross-sensitivity is unavoidable. Many IR measurements are cross sensitive to H2O, for example, therefore gases like CO2, SO2, and NO2 frequently cause cross sensitivity at low concentrations.

4 BEER LAMBERT LAW

The operating principle of NDIR gas sensor is governed by Beer Lambert Law.

4.1 LAMBERT LAW

When a beam of monochromatic light passes through an absorbing medium then its intensity decreases exponentially as the length of the absorbing medium increases.

$$I = I_0 e^{-kl}$$

4.2 LAMBERT BEER LAW

When a beam of monochromatic light passes through an absorbing medium then its intensity decreases exponentially as the length and concentration of the absorbing medium increases.

$$I = I_0 e^{-kcl}$$

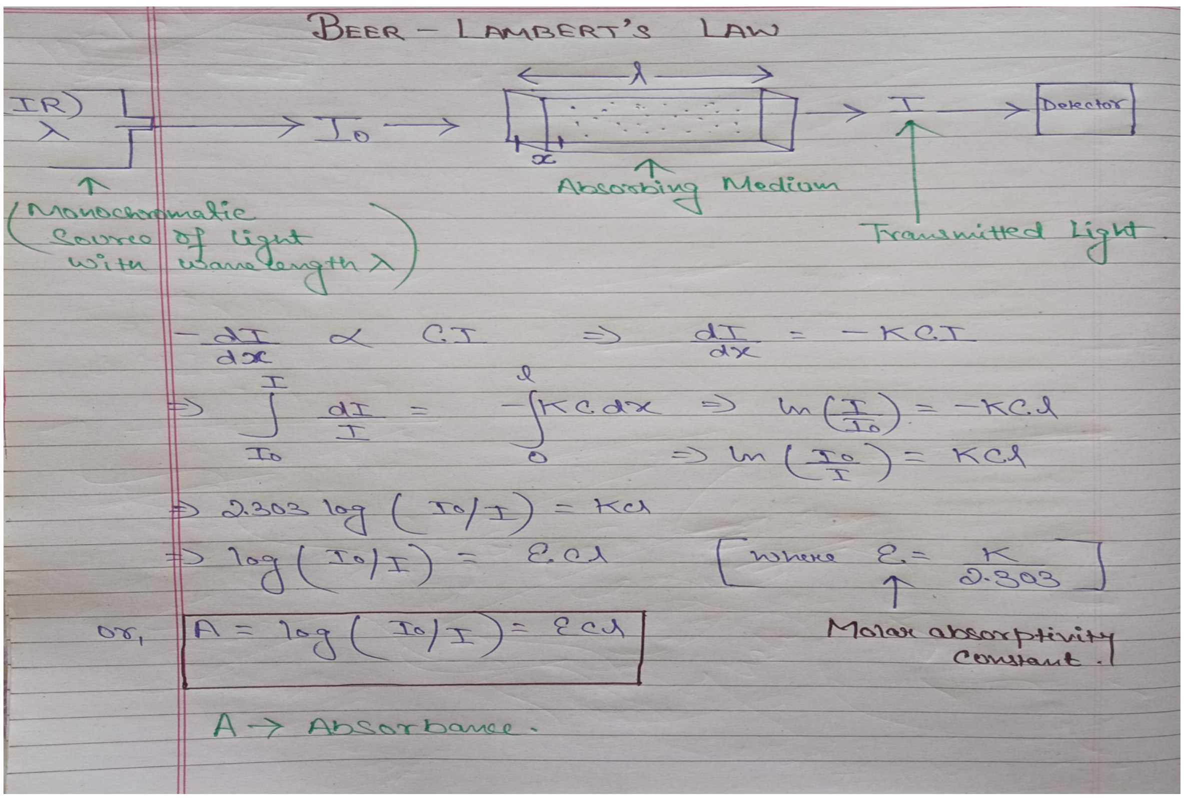

Figure 1: Derivation of Beer Lambert Law

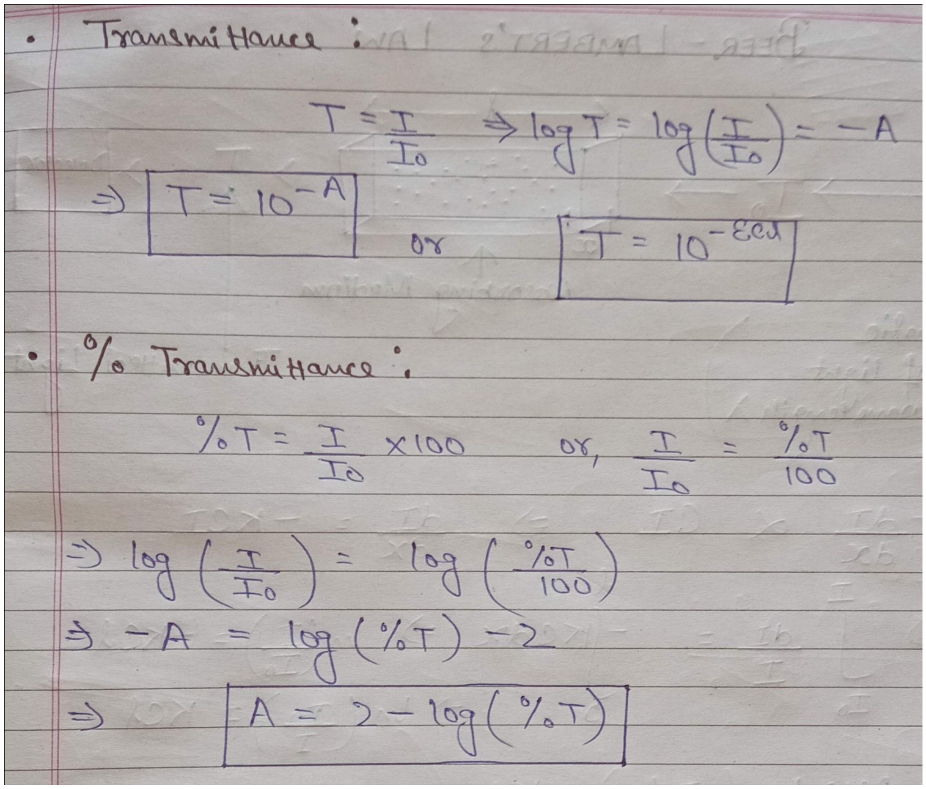

Figure 2: Calculation of Transmittance

5 OPERATING PRINCIPLE

When infrared radiation interacts with gas molecules, infrared light is absorbed by the gas molecules at a particular wavelength, causing vibration of the gas molecules. NDIR gas sensors detects the decrease in transmitted infrared light which is in proportion to gas concentration. This transmittance, the ratio of transmitted radiation energy to the incident energy, is dependent on target gas concentration.

NDIR gas sensor consist of an infrared source, detector, optical filter, gas cell, and electronics for signal processing. A single light source, dual wavelength type gas sensor has two detectors and two optical filters of different wavelengths which are placed in front of each detector. Infrared light that is absorbed by a target gas passes through the active filter with a particular bandwidth for the detection of the target gas. Infrared light that does not

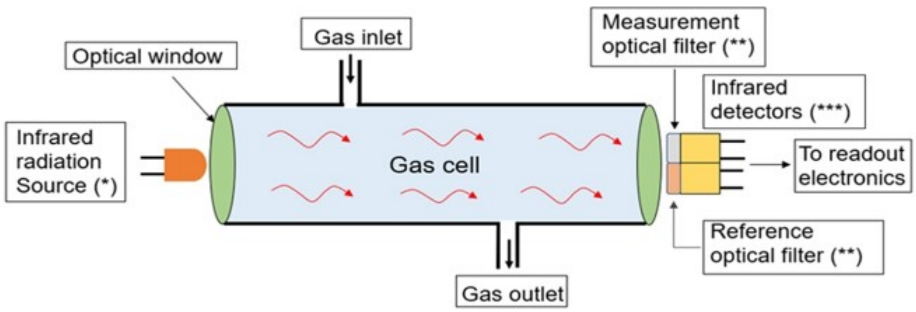

Figure 3: Schematic view of NDIR gas sensor

interact with the target gas passes through the reference filter. The difference between transmitted light intensities in these two bandwidths is converted into gas concentration.

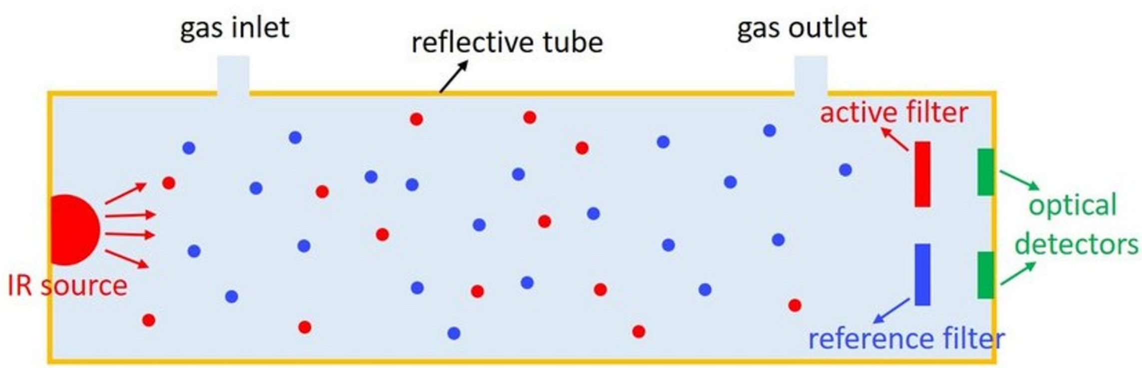

Figure 4: NDIR gas sensor using optical detectors

6 ABSORPTION SPECTRUM

Most of the gases absorbs the Mid infrared radiation from 2.5µm to 12µm. the gases like water vapour (H2O), Carbon di oxide (CO2), Carbon monoxide

(CO), Nitrogen di Oxide (NO2), Ozone (O3) etc absorbs the infrared radiation at a particular wavelength. From these absorption spectrum carbon di Oxide (CO2) absorbs the 4.2µm of wavelength in the Infrared radiation. In this project we use this wavelength to detect the Carbon di Oxide gas present in the chamber. From fig. 5, we observe that the absorption of IR radiation by CO2 gas molecules becomes maximum at 4.26 μm

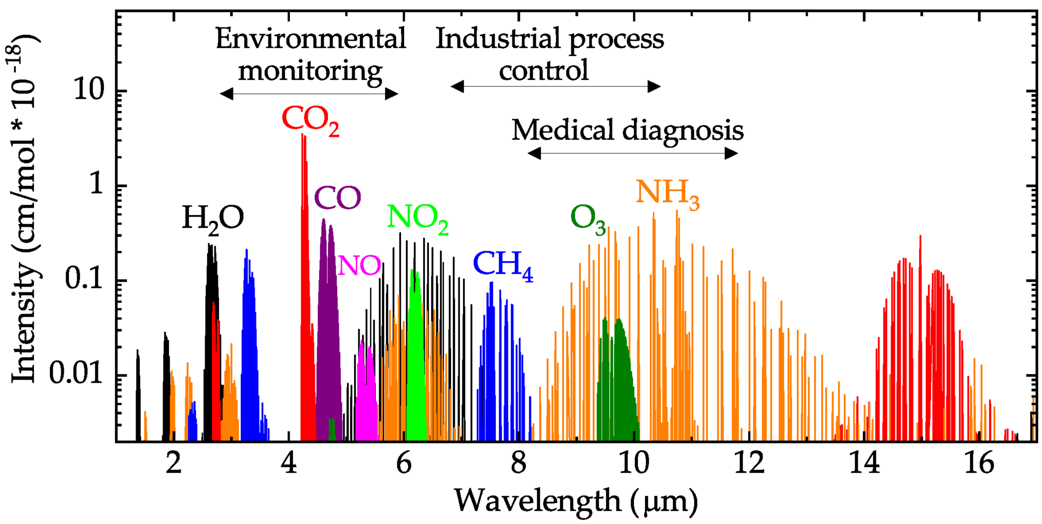

Figure 5: Absorption spectrum of different IR active gases

7 METHODOLOGY

We use the NDIR approach, based on optical gas sensing, leveraging the change in light intensity when CO2 gas molecules interact with light. As CO2 gas molecules have a characteristic absorption line in the mid-infrared (IR) spectral region, a drop in the transmitted signal due to CO2 gas molecules absorption is expected when light passes through the CO2 gas. This drop in signal will eventually be read as an electrical signal related to the gas sensitivity and CO2 gas concentration. The wavelength of 4.26 μm is chosen for CO2 gas absorption in this work as CO2 gas presents strong absorption peaks at wavelength of 4.26 μm[1]. This is also the mid-IR wavelength with minimal or negligible overlap of CO2 absorption peaks with other gases commonly present in ambient air. NDIR approach will work for gases like CO2 which are IR active, where a change in its dipole moment result in an oscillating electric field. The electric vector of the electromagnetic radiation which oscillates at the same frequency as the oscillating electric field due to change in dipole moment will be absorbed by the gas molecule. Atomic species such as argon (Ar) and homonuclear diatomics such as oxygen (O2) and N2 are not IR active and will not absorb IR radiation. Ar has only one atom and thus cannot exhibit a dipole moment. O2 and N2 have adjacent atoms with identical electro-negativities – vibration and rotation do not result in a change in their dipole moment. NDIR sensing requires a source emitting wavelengths at the absorption line of the targeted gas, and a detector for sensing the signal change. For the source, we chose a blackbody radiation source which emits a wide spectrum of wavelengths and hence can cover the absorption lines of many gases. By choosing appropriate optical filters, this blackbody radiation source could be used as the emitting source for detection of different specific gases. Using a blackbody radiation source with an appropriate optical filter is relatively low cost compared to using QCL and LED sources which emit only at particular wavelengths. In this paper, as we are detecting CO2 gas using CO2 absorption wavelength at 4.26 μm, an optical bandpass filter centered at wavelength of 4.26 μm is used. For the detector, we use our in-house fabricated ScAlN-based pyroelectric detector operating at room temperature and atmospheric pressure, and is able to detect over a wide range of spectral wavelengths.

Fig. 6 shows a schematic of the ScAlN-based pyroelectric detector that we use. The pyroelectric detector consists of a pyroelectric sensing layer with area 500 μm x 500 μm. We use 12 % doped ScAlN with thickness of 1 μm as the pyroelectric sensing layer[2]. On top and below the ScAlN sensing layer is the top and bottom electrodes respectively. Titanium nitride (TiN) is used as the top electrode and molybdenum (Mo) as the bottom electrode. Above TiN top electrode is a dielectric stack of silicon dioxide – silicon nitride – silicon dioxide (SiO2-SiN-SiO2) which acts as the absorber to help enhance light absorption into the device. This absorber stack is used to help broaden the absorption bandwidth with 3 layers of dielectric films and create destructive light wave interference in the stack for more efficient absorption. The top and bottom electrodes are connected to aluminum metal pads which act as metal contacts for electrical connections. Below the bottom electrode is a 1 μm thick SiO2 layer with waffle-like structures[3]. The SiO2 material helps to thermally isolate the thermal energy received by the pyroelectric detector sensing layer, slowing down thermal conduction to the medium below. In

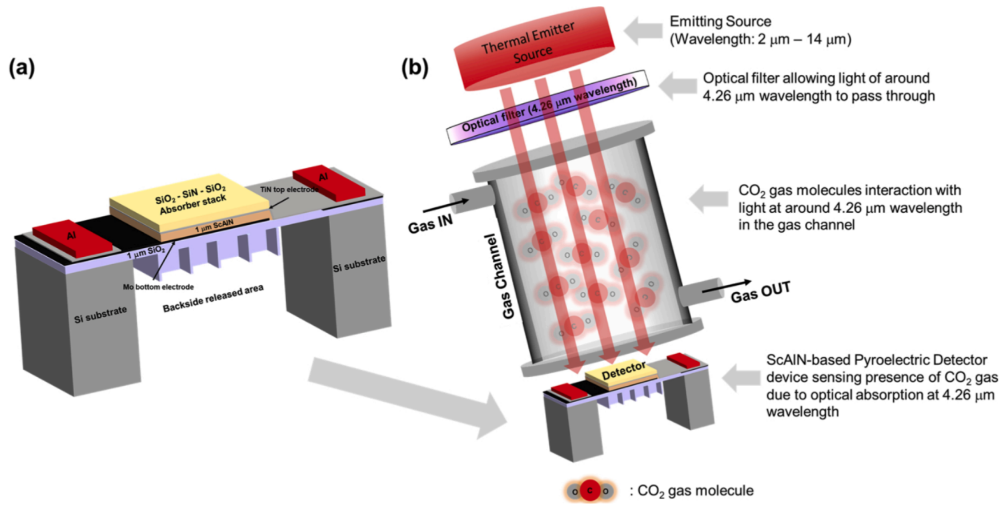

Figure 6: NDIR gas sensor using pyroelectric detector

addition, the Si substrate is released from the backside to form an air cavity area under the pyroelectric sensing region to further reduce thermal losses as air is a poor thermal conductor. The SiO2 waffle-like structures (also called SiO2 ribs) help to increase the mechanical stiffness of the pyroelectric sensing region which is in membrane form[4]. The fabrication steps of ScAlN-based pyroelectric detectors and their electrical characteristics are reported elsewhere in literature.

8 RESULTS

At different concentration of CO2 gas enclosed in a gas cell, we have obtained the percentage decrease in the intensity of IR radiation which is due to the absorption of IR radiation by CO2 gas molecules.

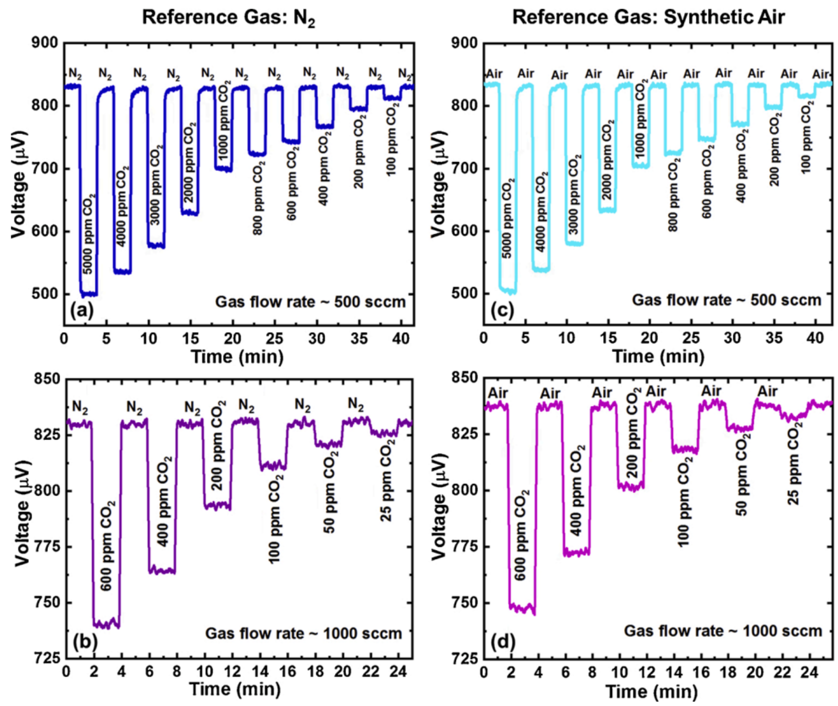

Figure 7: CO2 gas response at different conc. of CO2 gas

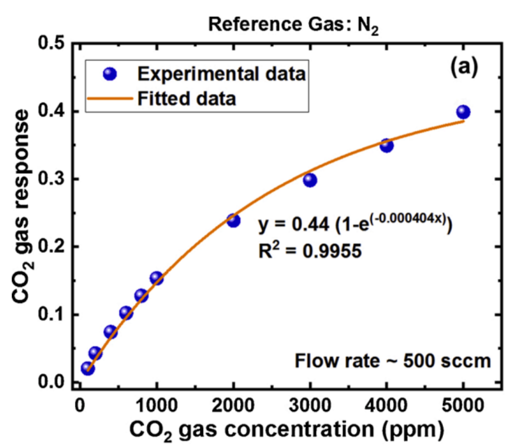

Figure 8: CO2 gas response with N2

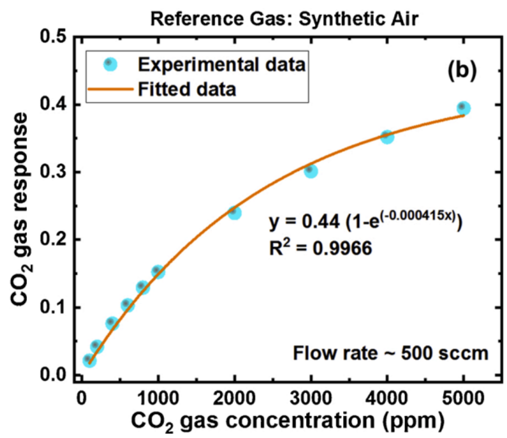

Figure 9: CO2 gas response with synthetic air

9 CONCLUSION

We have demonstrated NDIR gas sensing for CO2 gas using a CMOS compatible MEMS ScAlN-based pyroelectric detector. Using a blackbody thermal emitter source, an optical bandpass filter, a gas channel of length 10 cm and our in-house fabricated CMOS compatible MEMS ScAlN-based pyroelectric detector using 8-inch wafer technology with ScAlN deposition temperature at $200^{O}C$, we are able to sense changes in CO2 gas concentration from 5000 ppm, down to 25 ppm CO2 gas concentration. The different concentrations of CO2 gas are determined from the percentage change in the voltage signal when switching from the reference N2 gas or synthetic air to CO2 gas. CO2 gas responses measure 2% for sensing 100 ppm CO2 concentration and 40 % for sensing 5000 ppm CO2 gas concentration. The CO2 response times are measured when detecting 5000 ppm, 1000 ppm and 400 ppm CO2 gas concentrations in N2 and synthetic air respectively and the results show in general 2 s or lower. Humidity introduced to the CO2 gas up to 70 % relative humidity shows some minor effect (¡3%) to the CO2 gas response. Specifically, CO2 gas response seems to be most perturbed at 10 % relative humidity. The effect of humidity on CO2 gas response also seems to effect more on CO2 gas in N2 compared to CO2 gas in synthetic air[5]. These measured results could serve as guidelines for practical applications in NDIR CO2 gas sensing, and are promising for CMOS compatible MEMS ScAlN-based pyroelectric detectors used in NDIR gas sensing, opening further possibilities for low cost, wafer-level monolithic NDIR gas sensors with small footprints integrable with CMOS circuits.

References

[1] D. K. T. Ng, C. P. Ho, L. Xu, W. Chen, Y. H. Fu, T. Zhang, L. Y. Siow, N. Jaafar, E. J. Ng, Y. Gao, et al., Ndir co2 gas sensing using cmos compatible mems scaln-based pyroelectric detector, Sensors and Actuators B: Chemical 346 (2021) 130437.

[2] C. Ranacher, C. Consani, A. Tortschanoff, L. Rauter, D. Holzmann, C. Fleury, G. Stocker, A. Fant, H. Schaunig, P. Irsigler, et al., A cmos compatible pyroelectric mid-infrared detector based on aluminium nitride, Sensors 19 (11) (2019) 2513.

[3] G. Hyseni, N. Caka, K. Hyseni, Analysis of mwir infrared pyroelectric detectors parameters, in: Proceedings of the 5th WSEAS International Conference on Optics, Astrophysics, Astronomy (ICOAA '10), University of Cambridge, UK, 2010.

[4] A. Odon, Modelling and simulation of the pyroelectric detector using matlab/simulink, Measurement Science Review 10 (6) (2010) 195.

[5] X. Tan, H. Zhang, J. Li, H. Wan, Q. Guo, H. Zhu, H. Liu, F. Yi, Non-dispersive infrared multi-gas sensing via nanoantenna integrated narrow-band detectors, Nature communications 11 (1) (2020) 1–9.