Heliyon

Modeling of Gas Sensor based on Zinc Oxide Thin Films by Feedback Loop using Operational Amplifier

--Manuscript Draft--

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Abstract:	Gas sensing is seeking the attention of both industries and academia because of its wide-ranging application and intrinsic limitations of sensing technologies. Mostly, the gases are sensed due to variation in electrical, optical, acoustic, chromatographic, and calorimetric properties of sensing materials in the influence of various gases but in case of zinc oxide thin film, its resistance varies in influence to reducing gases [1, 2]. Particularly, this article is concerned in modeling durable sensing device using Zinc oxide thin film at low cost and operating within the low potential. To eliminate the temperature dependency for higher sensitivity of the sensor and fabricate cheap, portable, precise, less energy-consuming and durable sensing device, a new electronic model of the sensor was self-designed and analyzed. Monitoring the change in film's resistance, a perfect gas sensor was built. Zinc oxide thin film was synthesized by using the Sol-gel method (Spin coating) and was characterized by XRD and SEM which revealed wurtzite polycrystalline nature of Zinc oxide film with average grain size 17-25 nm. The fabricated film showed a fabulous response to ethanol and methanol vapors. It's the noble electronic model of gas sensing in the current time.
Opposed Reviewers:	
Additional Information:	
Question	**Response**
Publication ethics Please confirm that you have reviewed our guidelines for Ethics in Publishing as well as Heliyon's Ethics and Editorial Policies.	I confirm

Christian Schulz
Editorial Director
Cell Press Heliyon

Dear Schulz,

Warm greeting from Patan Multiple Campus and Nepal Academy of Science and Technology (NAST), Nepal. We would like to submit the manuscript entitled “Modeling of Gas Sensor based on Zinc Oxide Thin Films by Feedback Loop using Operational Amplifier” to be considered for publication as an original article in Sensors and Actuators.

Our research is concerned in modeling of gas sensor and we designed an unaccustomed electronic circuit, modeled it theoretically, and then experimentally verified that the circuit performs well by using Zinc oxide thin film as sensing material in the circuit.

We declare that our findings are completely novel till date and no such articles have been published in any of the journals before. Furthermore, we would like to apprise that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We are known that this publication has no conflicts of interest associated and there hasn’t been any financial support for this research that could influence its outcomes. As a corresponding Author, I would like to confirm that the manuscript has been read and approved for submission by all the authors.

Sincerely,
Raju Bhattarai

Conflicts of Interest Statement

Manuscript title: MODELLING OF GAS SENSOR BASED ON ZINC OXIDE THIN FILMS BY FEEDBACK LOOP USING OPERATIONAL AMPLIFIER

The authors whose names are listed immediately below certify that they have **NO** affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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This statement is signed by all the authors to indicate agreement that the above information is true and correct.

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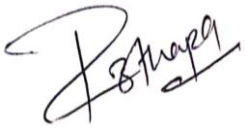
Ram Bahadur Thapa		2 Sep 2023
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About the revision

Christian Schulz

Editorial Director

Cell Press Heliyon

Dear Schulz,

Manuscript entitled **"Modeling of Gas Sensor based on Zinc Oxide Thin Films by Feedback Loop using Operational Amplifier"** had been sent back for revision. We want to greet heartily the reviewers for their valuable reviews and apologies for inconvenience and commend the following edition as per the reviewer's suggestion for the publication of the article.

1. Data will be made available whenever asked.

2. **Reviewer #1:**

(a) The authors of the study claimed that their sensor was better, but failed to provide a comparative analysis. It would be useful to compare their work with the widely used chemi-resistive gas sensors, like MQ sensors, which are based on potential divider networks. This would allow readers to better understand the effectiveness of the sensor fabricated in the study.

Replied: As suggested, we have compared our sensor with MQ-sensors referencing concerned article. MQ sensor uses heating mechanism to heat its sensing material around 300 ^{o}C but we do not need to heat the film to sense the gases. (P2 last paragraph)

(b) In Figure 3, connections are not proper.

Replied: All the connections are proper. It is obvious that the amplifier should be connected to Vcc ans ground.

(c) In order to ensure transparency and reproducibility, authors are advised to include the code number of the amplifier used in their research.

Replied: Most of the amplifier fits well in the circuit. We have not included the code here so as to save the article and findings from being copied. After publication, it can be made available if asked.

(d) If possible, merge Figure 8 with Table 2 for clarity.

Replied: Figure 8 and Table 2 have been merged as per suggestion.

(e) Repeatability is an important parameter for the gas sensing device. It is recommended that authors include repeatability measurements for a minimum of three cycles.

Replied: We have passed different concentrations of alcohol vapors (Ethanol and Methanol) through the same sample of thin film and have stated the response and recovery time too. We have conducted multiple experiments and noted the similar data. Presenting same or similar data for multiple times may not look good. So we represented the data of various concentrations of Ethanol and Methanol once.

(f) It is recommended that the authors make some corrections to their manuscript, specifically addressing errors such as the following:

In P2L41, provide a space in "Solutionwas"

In P2L42, change 'ml' to 'mL'

In P7L48, do not capitalize the first alphabet of trigonometric functions.

Replied: All of these are corrected.

3. **Reviewer #2:**

The manuscript deals with the elimination of the temperature dependency for higher sensitivity of the metal oxide gas sensor and fabrication of a cheap, portable and durable sensing devices and a new electronic circuit, a perfect gas sensor.

"Zinc oxide thin film was synthesized by using the Sol-gel method (Spin coating) and was characterized by XRD and SEM which revealed wurtzite polycrystalline nature of Zinc oxide film with average grain size 17-25 nm.

Please explain what does it mean?

Replied: As these been stated in an abstract, we have explained all these in introductory, characterization, result and discussion section. For example, in last paragraph of "Introduction" Section, we have discussed dependency of sensing material of MQ-sensor in temperature for sensing the gases.

4. **Editor comment:** This work presents a design of an electronic circuit made specifically for a sensor system. In order to be acceptable as a scientific article the manuscript needs to go beyond a technical report of a sensor, reporting scientific advances in sensor science (not only development of a circuit). Please revise the manuscript and make sure that it goes beyond a technical report of a sensor circuit and emphasize the contribution to scientific advance.

Replied: The manuscript has been revised. It is not just a technical report. It has described the way to synthesize the ZnO thin film in a unique way and has characterized it. It explains the use of ZnO as a thin film sensor. It claims the sensor performs better than other and verifies experimentally. Thus, it is scientific work.

Sincerely,

Raju Bhattarai

Modeling of Gas Sensor based on Zinc Oxide Thin Films by Feedback Loop using Operational Amplifier.

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[1]*Patan Multiple Campus, Department of Physics, Patandhoka, Lalitpur*

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Abstract: *Gas sensing is seeking the attention of both industries and academia because of its wide-ranging application and intrinsic limitations of sensing technologies. Mostly, the gases are sensed due to variation in electrical, optical, acoustic, chromatographic, and calorimetric properties of sensing materials in the influence of various gases but in case of zinc oxide thin film, its resistance varies in influence to reducing gases [1, 2]. Particularly, this article is concerned in modeling durable sensing device using Zinc oxide thin film at low cost and operating within the low potential. To eliminate the temperature dependency for higher sensitivity of the sensor and fabricate cheap, portable, precise, less energy-consuming and durable sensing device, a new electronic model of the sensor was self-designed and analyzed. Monitoring the change in film's resistance, a perfect gas sensor was built. Zinc oxide thin film was synthesized by using the Sol-gel method (Spin coating) and was characterized by XRD and SEM which revealed wurtzite polycrystalline nature of Zinc oxide film with average grain size 17-25 nm. The fabricated film showed a fabulous response to ethanol and methanol vapors. It's the noble electronic model of gas sensing in the current time.*

Keywords: Miniatured sensing device, less energy consuming, noble electronic model.

I. Introduction

Currently, gas sensing is tugging the attention of both industries and academia because of its wide-ranging application in the areas like industrial production (e.g., detection of methane in mines), automotive industry (e.g., detection of pollutant gases from vehicles), medical applications (e.g., electronic noses simulating the human olfactory system), supervision of indoor air quality (e.g., carbon monoxide detection), environmental studies (e.g., monitoring greenhouse gas). Since the last sixty years, researches have been focused on investigation of different types of sensing materials, sensing mechanism and, fabrication techniques of sensing materials. Those researches revealed various fabrication techniques, introduced several sensing materials (e.g., different metal-oxides, polymers), and different approaches of sensing mechanism [1].

Mostly, the gases are sensed by the particular materials due to variation in electrical, optical, acoustic, chromatographic, and calorimetric properties of sensing materials in influence of various gases. In context of metal oxide semiconductor thin films, nanotubes, and polymers electrical property, i.e. resistance of the film varies due influence of respective gases [2]. Monitoring this change in value of resistance of the film, a perfect gas sensor can be built.

The way that the traffic police takes a breathalyzer test in Nepal (going closer to the subject and asking to blow air from mouth then smelling it) has motivated us to conduct research on the gas sensing device so that we could contribute to our nation. So, particularly this article is concerned in modeling durable sensing device at low cost, and operating within the low potential. Most of the metal oxide-based gas sensors are too expensive and need to be maintained at a certain value of operating temperature for higher sensitivity. For instance MQ-sensors use their inbuilt heating system to heat the reducing gases around the sensing material in the range of 200 ^{o}C - 300 ^{o}C for

sensing. It alone cannot sense the gases, rather it should be connected with Aurdino UNO and cannot be operated with small battery source. It requires huge warm up time to work well [3]. To eliminate this temperature dependency for higher sensitivity of the sensor and to fabricate cheap, portable, precise, less energy consuming and durable sensing device, new model of sensor is designed and analyzed. It's one of the emerging and demanding techniques of gas sensing in the current time.

II. Methodology

Gas sensing properties of various metal oxide semiconductors were studied through published journals and variation in resistance of different materials were noted. Different electronic circuits were designed using CircuitMod 2.7 and Online Circuit Simulator and Schematic Editor-Circuit Lab. Then the variation in output of the designed circuit due to change in resistance of the variable resistor (Thin Film) was tabulated and analyzed. For the experimental verification, single coated Zinc Oxide thin films were fabricated using spin coating method.

Fabrication of thin film:

There are more than dozens of methods: Laser ablation, High energy ball milling, Physical vapour decomposition, Melt mixing, Sputter deposition, Electric arc deposition, Ion implantation, Precipitation method, Co-precipitation method, Colloidal methods, Sol-gel processing (Spin coating, Dip coating, and Spray pyrolysis), Water-oil micro-emulsion method, Hydrothermal synthesis, Solvothermal, Sono-chemical synthesis, Polyol methods, Vapour phase fabrication, etc for thin film fabrication [4, 5]. Because of its simplicity, reliability, and accessibility, we found Spin Coating method being feasible within our budget and lab frame too.

Spin Coating is the most preferred technique for the thin film deposition on the flat substrate due to its plainness, low cost, easy doping, low operating temperature, and spin and film thickness controllability. A very small amount of coating material is dropped at the centre of the substrate spinning at a constant speed or at rest, then is rotated at high speed to spread the material uniformly all over the substrate. As soon as, the coating is completed, the substrate is annealed for the evaporation of the unwanted solvent and deposition of the film. The process is continued until the desired thickness or resistance of the film is achieved [6, 7].

Glass substrates were cut into square pieces (2.5cm x 2.5cm), washed with distilled water then sonicated for 15 minutes with distilled water and Acetone at 70^{o}C then dried in a hot air oven at 100^{o}C. For 0.5 M precursor solution (Solution for pure ZnO thin film), 13.3872 g of Zinc Acetate Dihydrate (ZAD) and 6mL of Diethyl Amine (DEA) added to 120 mL of Ethanol was stirred at 300 rpm for an hour at room temperature. 0.1 mL of precursor solution was spread over the spinning (at 3000 rpm for 30 seconds) substrate in a spin coater and was annealed over the hot plate at 550^{o}C for 15 minutes.

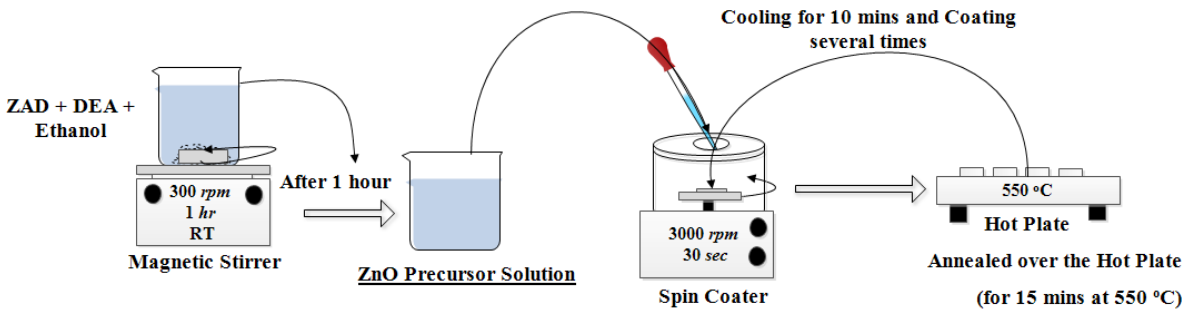

Figure 1: Preparation of ZnO thin film by Spin Coating Method.

The films fabricated were further cut into minute pieces (4 mm x 7 mm) and heated at 100°C for 2 hours. As soon as the film gets heated, thin insulated wires-conducting at the ends were connected to both the ends of the film using Silver paste. Two heating system was adjusted at the ends of a cylinder of the volume of about 300 cm^3; heater at the top was to monitor the temperature of the film (if necessary) and heater at the bottom was to evaporate liquid (if necessary). The needle of the syringe was adjusted as shown as in the figure below so as to pass gas or drop liquid over the heater. This is the way, how we built a setup for the exposure of thin film to gas for sensing purpose.

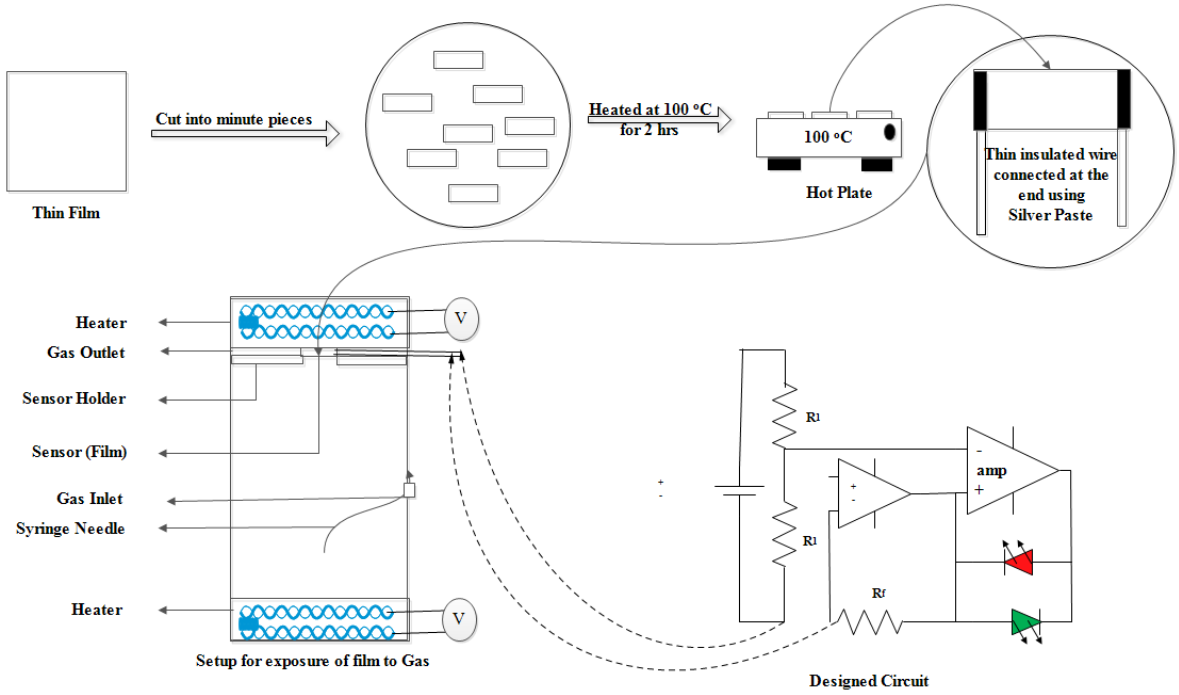

Figure 2: Entire setup for sensing**.**

Different concentration of ethanol and methanol was passed into the chamber, and corresponding response of the circuit was observed and noted.

Circuit (Sensor) Designing:

Several electronic circuits were designed using CircuitMod 2.7 and Online Circuit Simulator and Schematic Editor-Circuit Lab, and variation of outputs due to variation in resistance of thin film used in the circuit was analyzed. Then the necessary electronic components were fixed in the PCB board.

Two resistors (R_1 and R_2) were connected in series with 3 V battery. The positive input terminal of first amplifier was connected to R_2, negative input terminal was grounded through film and output terminal was connected to its negative input terminal through a feedback resistor (R_f). In case of second amplifier, its negative input terminal was connected to R_1, positive input terminal was connected to output terminal of first amplifier and its output terminal was connected to its positive input terminal through two light emitting diodes (LEDs; one red and another green) in parallel and opposite configuration (positive end of red LED connected to negative end of green LED and vise-versa). The seventh pins of both amplifiers were connected to positive terminal of source; fourth pins were grounded, whereas first and eighth pins were left floating. Also, a bugger was connected in series with red LED.

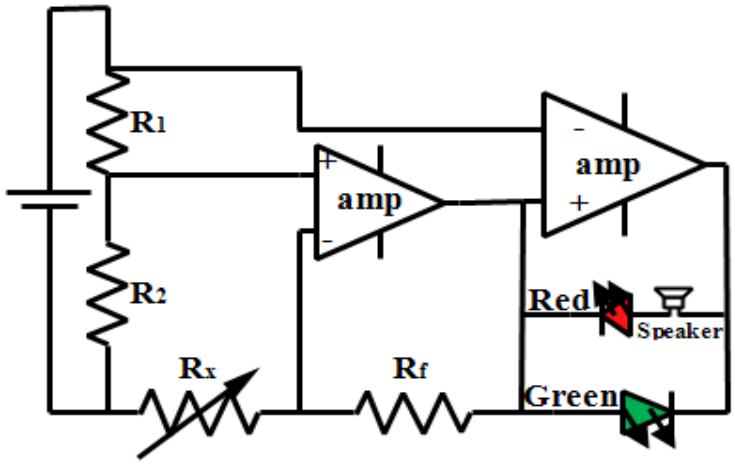

Figure 3: Designed Sensor Circuit where R_x is film resistance.

Also, the configuration works if the both amplifiers and LEDs are flipped in respect to polarity.

Sensing Mechanism:

The detection mechanism of Semiconductor Metal Oxide (SMO) as a sensor is complex and not yet fully understood. Adsorption ability, electrophysical and chemical properties, catalytic activity, thermodynamic stability and the adsorption/desorption properties of the surface of SMO as well yields this complexity [1]. ZnO (n-type semiconductor) thin film surface, when exposed to air, adsorb oxygen molecules to form molecular type adsorbate (O_2, O_2^-) and dissociative type (O_2^{2-}) adsorbate ions forfeiting electrons from the conduction band, yielding electron-depleted space-charge layer in the grain boundary region which leads to large surface potential barrier and large resistance. The target gas (ethanol/methanol) may undergo dehydration and dehydrogenation and successively oxidized to CO, CO_2, and H_2O, but ZnO being basic oxide, dehydrogenation is favored. The response of the film towards alcohol vapors is dependent on the conversion of alcohol into aldehydes [7, 8].

$$2C_2H_5OH \rightarrow 2CH_3CHO + H_2 \quad (1)$$

$2CH_3CHO\ (ad) + 5O_2^{2-}\ (ad) \rightarrow 4CO_2 + 4H_2O + 10e^-$ (2)

$2C_2H_5OH\ (ad) + O_2^{2-}\ (ad) \rightarrow 2C_2H_4O^-\ (ad) + 2H_2O$ (3)

$C_2H_4O^-\ (ad) \rightarrow CH_3CHO\ (ad) + e^-$ (4)

$CH_3OH\ (g) \rightarrow CH_3OH\ (ad) \rightarrow CH_3O\ (ad) + H(ad)$ (5)

The release of electrons back to the film enhances the conductivity of the film and deduces the resistance [8]. When oxygen adsorbed onto the film surface which traps electrons from the bulk of material forming a potential barrier is replaced by reducing gas molecules the barrier at the grain boundaries decreases and thus reduces the electrical resistance of the film [1]. This reduces potential at the negative input terminal of the first amplifier which yielding change in its output and potential at the positive input terminal of the second amplifier. This change in the value of positive input of the second amplifier changes the polarity of its output from negative to positive and current flows through red LED only. So, only red LED glows and bugger beeps.

In the former case (when the film is not exposed to reducing gas), the circuit yields negative output so red LED being reverse biased blocks electron to flow through it and only green LED being forward biased allows flowing current through it and glows. As soon as the vapor passes away, the film undue starts adsorption of atmospheric oxygen and tends to achieve its former state [8]. And, again the circuit glows Green as soon as the film recovers.

III. Results and Discussion

UV-Vis Spectroscopy:

The optical characterization of the samples was performed in Nepal Academy of Science and Technology (NAST) using UV-Vis spectrophotometer (Carry 60 spectrophotometer, Agilent Technology). The absorbance, and transmittance of the films were measured which were further analyzed to calculate the band gap and thickness of the films. For indirect transition, the variation in absorption coefficient with the photon energy obey Tauc's plot method,

$$(\alpha h\nu)^{0.5} = A(h\nu - E_g) \quad \text{(Eq. 1)}$$

Where A is a constant, E_g is the optical band gap, h is the plank constant and α is the absorption coefficient. Extrapolation of $(\alpha h\nu)^{0.5} = 0$ yields the optical bandgap energy of the films [9].

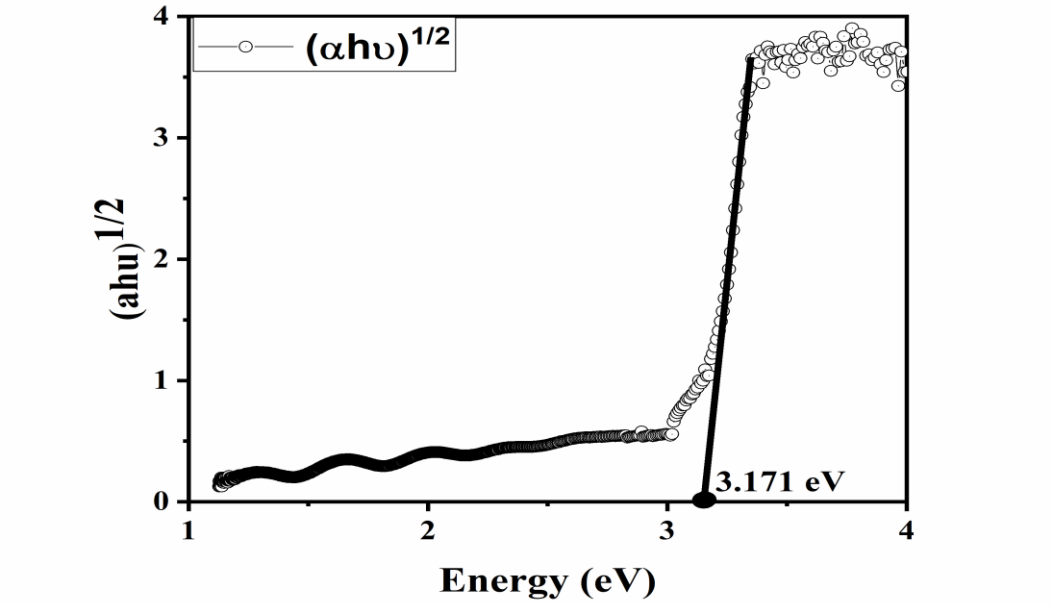

Figure 4: Tauc's Plot for calculation of Energy Bandgap

The bandgap of thin film fabricated by us was found to be 3.171 eV.

X-ray Diffraction (XRD):

The dual natured (behaving as both particle and wave) electromagnetic radiation having high penetration power[6], photon energy within 100 eV- 100 KeV is termed as X-ray. It is a non-destructive technique used for characterizing crystalline substance. This helps in the identification and quantification of the crystalline phase, structure, orientation, composition, and defects. Further, it is used to measure the size, strain or micro-strain effects, transparency and electron mobility in thin-films [10]. The structural characterizations of fabricated thin films were analyzed using XRD [Bruker D2 Phaser X-ray diffractometer of CuKα radiation (wavelength: 1.54184 Å)] at 40 KV of operating voltage and current of 40 mA in the 2θ range of 20° - 80° at scanning rate of 15° per minute at NAST, Khumaltar, Lalitpur, Nepal. The Debye Scherrer's formula used to calculate the average grain size 'D' is given by,

$$D = \frac{0.9\lambda}{\beta cos\theta} \quad \text{(Eq. 2)}$$

where, 0.9 is the correction factor, λ is the wavelength of the x-radiation, β is the full width at half maximum (FWHM) of the observed peak and θ is the Bragg's angle [10]. Comparing calculated d-spacings with the standard JCPDS values of card number 36-1451, the observed peaks were indexed. The average crystallite size of ZnO was found to be 20.068 nm using Scherrer's method.

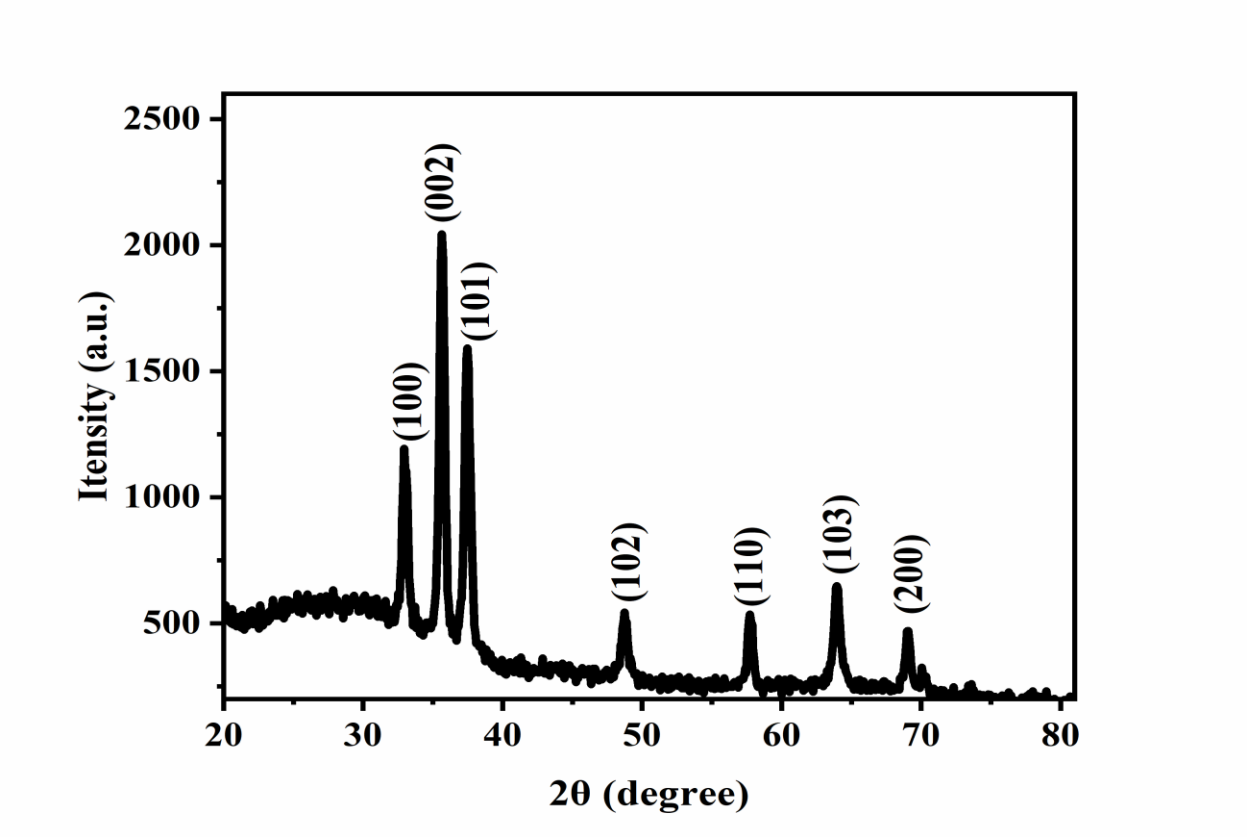

Figure 5: XRD pattern of Pristine ZnO thin film.

The crystallite size of as deposited ZnO thin films were also calculated using W-H plot method using prominent XRD planes then compared with that obtained from Scherrer's formula. The W-H plot is related with the full width half maxima (FWHMs) (β) of XRD peaks and crystallite size(D) through the relation,

$$\frac{\beta\cos\theta}{\lambda} = \frac{1}{D} + \frac{4\varepsilon\sin\theta}{\lambda} \qquad \text{(Eq. 3)}$$

Where, ε is the amount of residual strain, θ is the angle of diffraction, λ is the wavelength of X-ray [10]. A graph between βcosθ/λ versus 4sinθ/λ when plotted and fitted linearly, the reciprocal of the x-intercept gives the average crystallite size [11] and was found to be 17.345 nm.

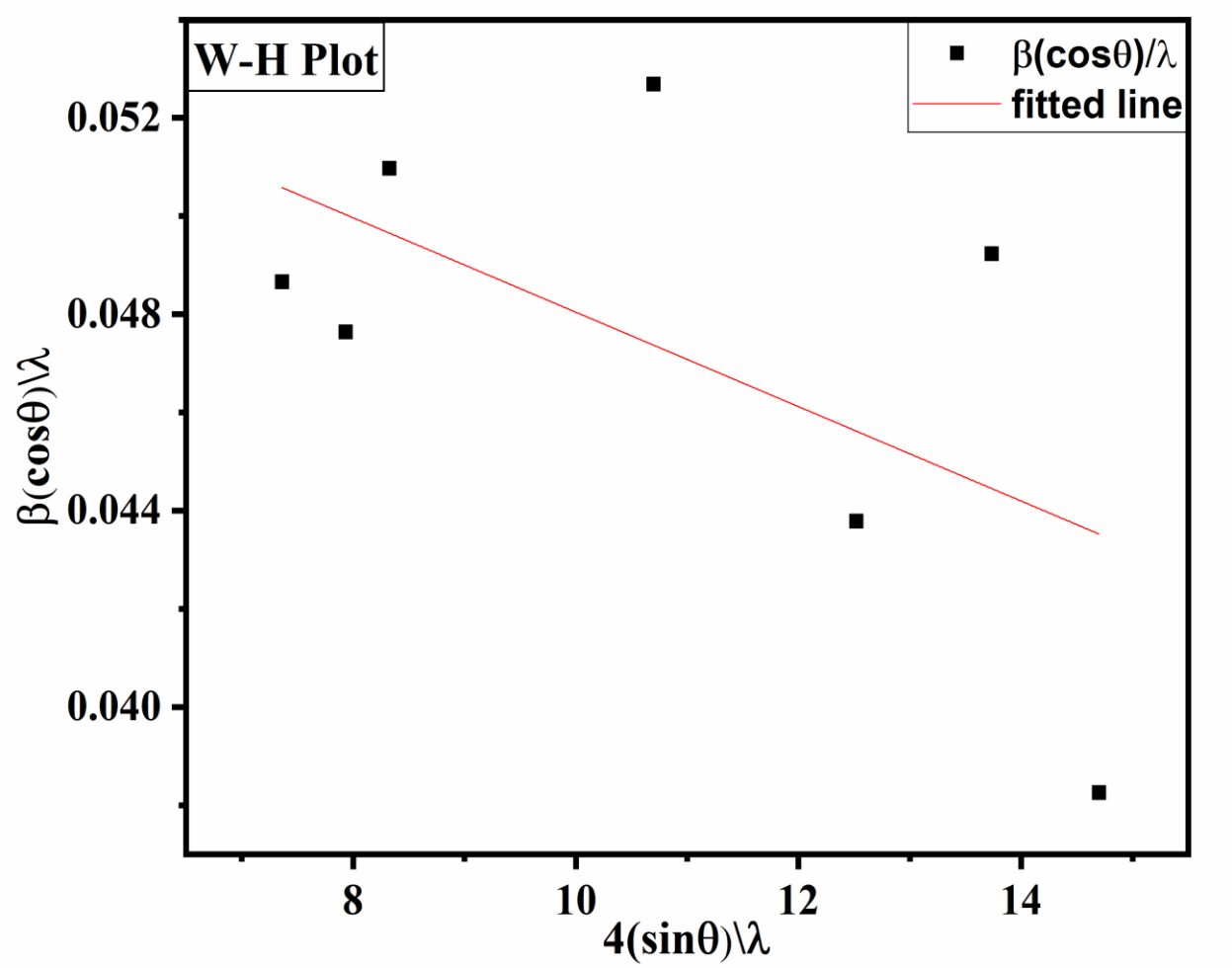

Figure 6: William-Hall (W-H) plots of pristine ZnO.

The crystallite size of the fabricated film calculated from the W-H plot was found consistent with that as calculated from Scherrer's method.

Table no 1: Shows XRD analysis for miller indices, d-spacing, and grain size of the deposited ZnO thin film.

S.N.	Miller Indices	Angle 2θ	Calculated d (Å)	JCPDS(36-1451) d (Å)	Crystallite Size D(nm)	
					Scherrer's Method	W-H plot
1.	(100)	32.95075	2.7172	2.8142	19.31788	Average
2.	(002)	35.60633	2.5204	2.6033	19.73324	
3.	(101)	37.42934	2.4018	2.4759	18.44347	
4.	(102)	48.69692	1.8692	1.9111	17.84351	20.0678 17.3445
5.	(110)	57.69607	1.5972	1.6247	21.46739	
6.	(103)	63.92009	1.4559	1.4771	19.09518	
7.	(200)	69.00289	1.3605	1.4072	24.57326	

Scanning Electron Microscope (SEM) and EDX analysis:

The surface morphology of ZnO thin films were performed using Scanning Electron Microscope at Research Centre for Eco-Environment Sciences, Chinese Academy of Sciences, Beijing, China.

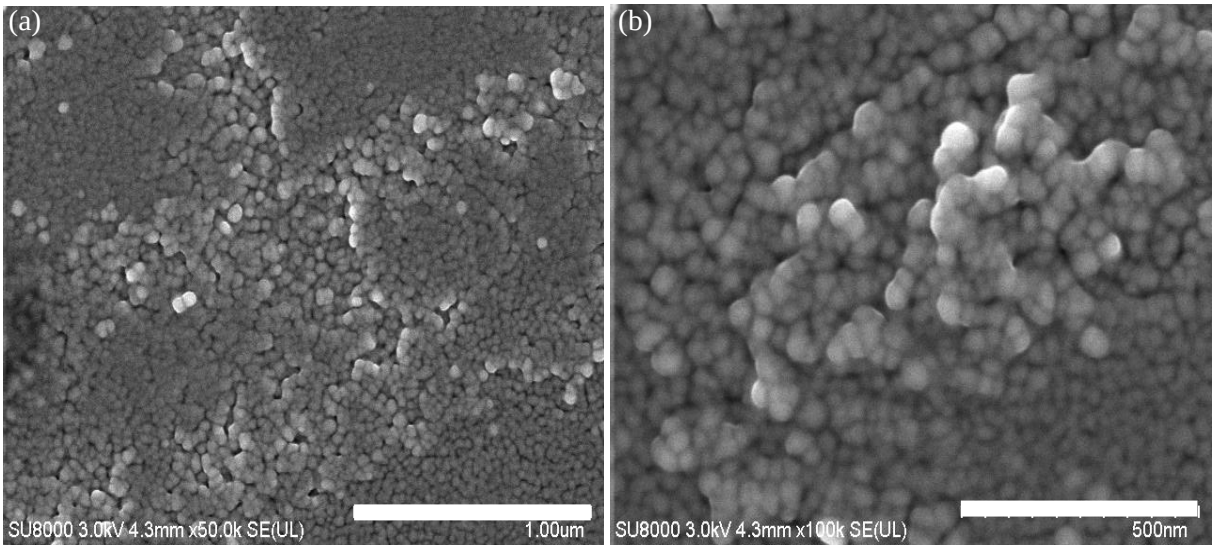

Figure 7: SEM images of ZnO thin film with scale (a) 1µm and (b) 500nm

Figure 7(a) and 7(b), shows the SEM images of undoped ZnO with scale 1µm and 500nm and magnification of 50K and 100K respectively. The SEM image depicts grainy structure of film. The average grain size of ZnO was found to be around 25 nm which is quite corresponding to results obtained from XRD analysis.

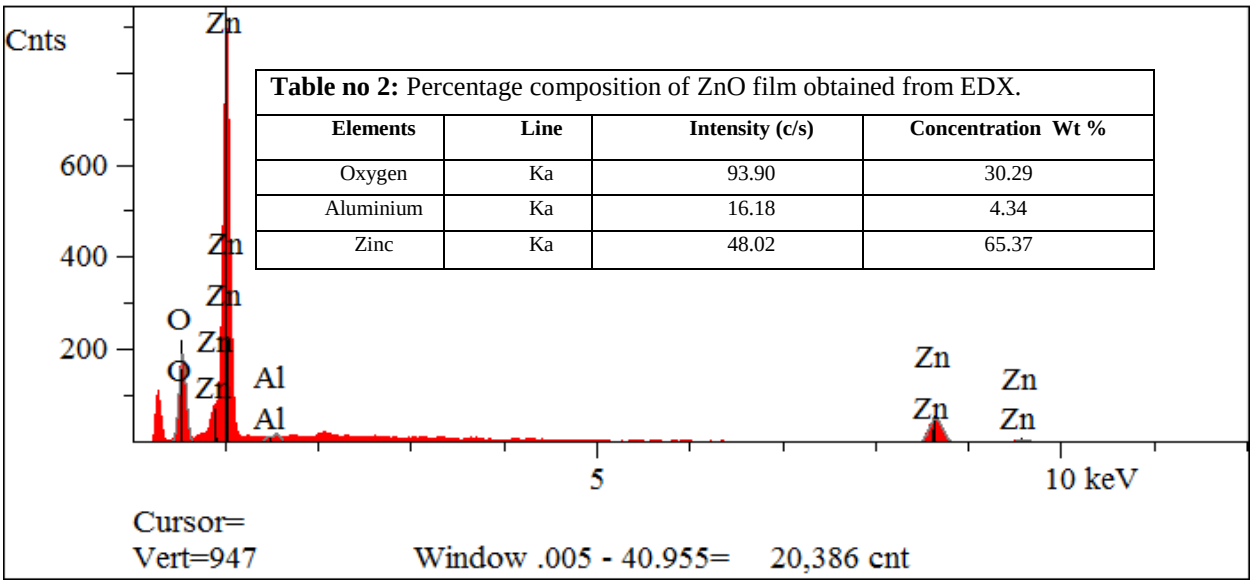

Table no 2: Percentage composition of ZnO film obtained from EDX.

Elements	Line	Intensity (c/s)	Concentration Wt %
Oxygen	Ka	93.90	30.29
Aluminium	Ka	16.18	4.34
Zinc	Ka	48.02	65.37

Figure 8: Energy Dispersive X-ray image of Pristine ZnO film.

Figure 8 shows the EDX spectra which assure that the film is of Zinc oxide. Very small peak of Aluminium is detected which may be due to Aluminium silicate (glass) substrate. The EDX spectrum of ZnO sample shows the high content i.e. 65.37 wt. % of Zinc, 32.29 wt. % of Oxygen and 4.34 wt. % of Aluminium which is almost negligible compared to oxygen and Zinc.

Circuital Analysis:

The circuit designed is the novel concept in sensing gas. Since the resistance of the film is influenced by material used for depositing thin film, the number of coating done, doping in film, and aging of the film, the values of the resistors used in the circuit must be different for different value of film resistance at the ordinary condition. These values of the components must be appropriate to determine or sense the selected reducing gas. Here we present some particular values of these components and the critical point value of film resistance for the particular configuration of the circuit. The critical point value is the value of film resistance beyond which the output voltage of the circuit changes its polarity or the LEDs switch.

Table no 3: Shows the values of Components to be used in accordance to film resistances and selected gas.

S.N.	Feedback Resistance R_f (KΩ)	Ratio (R_1: R_2)	Critical Point Value (KΩ)	Best Range of Film Resistance R_x	Minimum Sensitivity S (%)
1.	560	1:3	1679	(2-1.7) MΩ	(15-1.24)
	560	1:10	5999	(50-6) MΩ	(22-0.02)
	560	1:100	55899	(200-56) MΩ	(72-0.18)
2.	470	1:3	1410	(2-1.5) MΩ	(30-5)
	470	1:10	4759	(15-5) MΩ	(67-4.82)
	470	1:100	46899	(200-47) MΩ	(77-0.22)
3.	100	1:3	298.99	(400-300) KΩ	(25-0.34)
	100	1:10	999.79	(2-1) MΩ	(50-0.021)
	100	1:100	9982.56	(40-10) MΩ	(75-0.174)
4.	10	1:3	44.98	(80-45) KΩ	(44-0.04)
	10	1:10	99.98	(300-100) KΩ	(67-0.02)
	10	1:100	997.92	(3-1) MΩ	(67-0.02)
5.	1	1:3	2.999	(5-3) KΩ	(40-0.03)
	1	1:10	9.998	(30-10) KΩ	(67-0.02)
	1	1:100	99.82	(300-100) KΩ	(67-0.18)

Table no 3 represents the theoretical values for the circuital components for sensing the selected gas to approximate the appropriate value of feedback resistor, the ratio of R_1 and R_2 to be used in the circuit for sensing particular gas within a limited range of sensitivity.

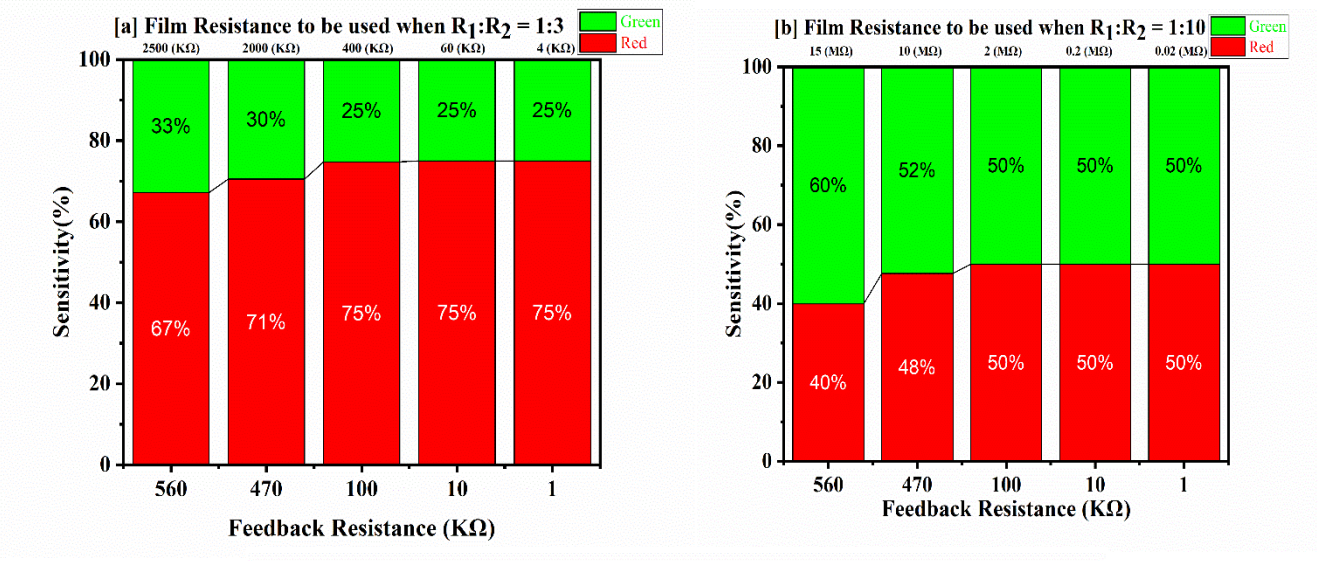

Figure 9: Sensitivity Stacked Chart for different ratio of R_1 and R_2 (a) 1:3, (b) 1:10 and (c) 1:100 and different values of Film and Feedback Resistances.

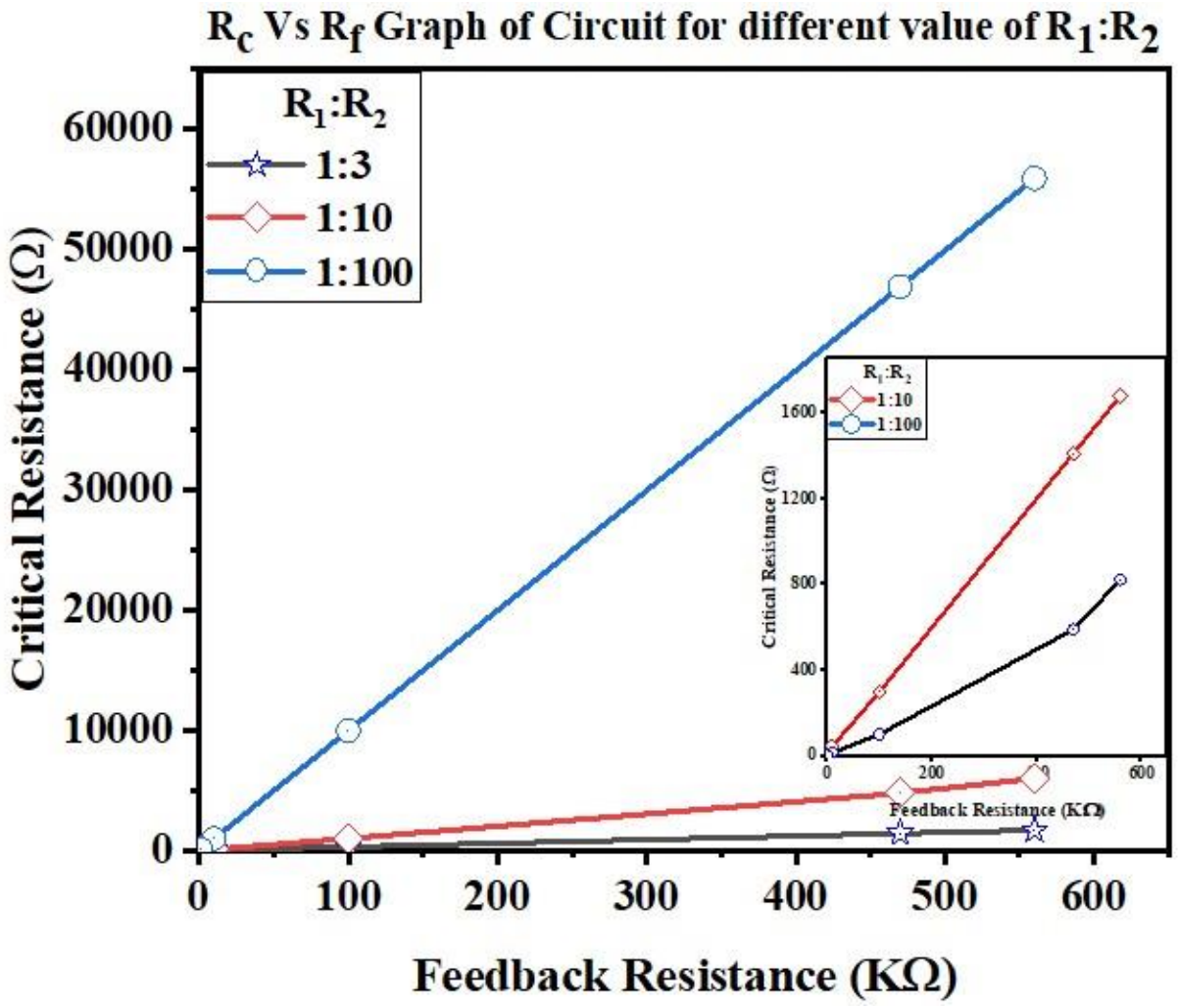

Figure 10: Critical vs feedback resistance graph at different ratio of R_1 and R_2.

Figure 10 clearly depicts that critical point value or the critical resistance of the film is linearly dependent on the feedback resistance used in the circuit for same R_1:R_2. The critical resistance is such value of the film above which the circuit glows Green and below which results glowing Red. Also, it suggests that increment in the ratio R_1:R_2 yields higher value of critical resistance which will be very efficient for using highly resistive film as a sensor. Lower value of R_1:R_2 gives lower value of critical resistance which will be more effective if used with less resistive film. Furthermore, highly resistive film can be used as sensor along with lower value of R_1:R_2 if the target gas highly reduces the film below critical value. The mechanism is same for feedback resistor. Thus, appropriate value of R_1:R_2 and feedback resistor can let us sense reducing gas of any concentration.

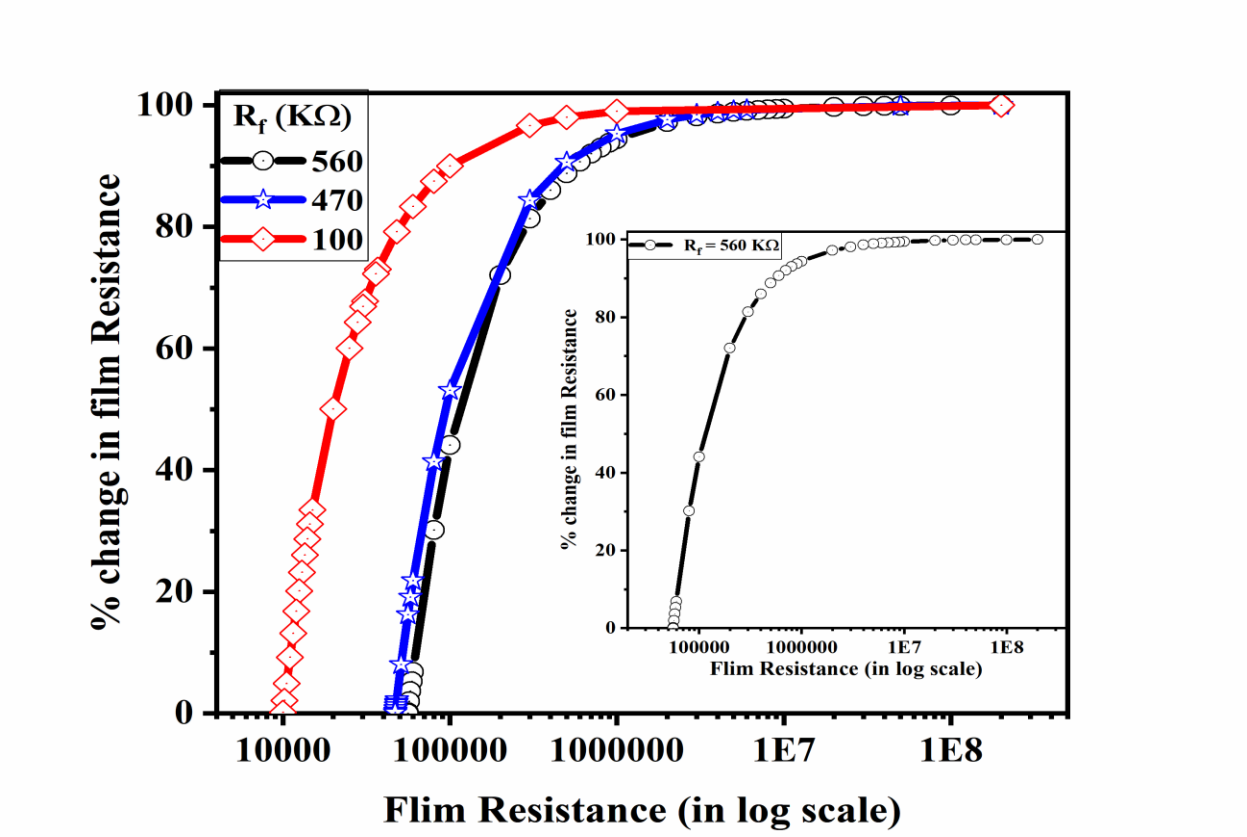

Figure 11: Least percentage change of Film Resistance required for sensing vs Film resistance graph gor different value of R_f.

Figure 11 is the plot of film resistance (in log scale) vs least percentage change required for sensing the target gas at different value of feedback resistance for R_1:R_2 equals 1:100. The graph clearly shows that highly resistive film needs more than 90% change in their film resistance for sensing (RED glow in circuit) in above mentioned configuration. But Film resistance closer to the critical value of resistance can sense well within less percentage change in its former value. This circuit best suits for sensing even if the target gas increases the film resistance. But selecting appropriate and accurate R_1:R_2, feedback resistor and remaining circuital components is most for excellence performance.

Thus, analyzing Figure 10 and Figure 11, we can conclude that sensitivity of the circuit is dependent on the value of critical resistance of the film but not on the film resistance. This is the most fantabulous characteristics of the circuit which overcomes the dependency of the available ordinary sensors on film resistance. Furthermore, the critical value of the film is controllable. It depends upon the components used in the circuit. The film resistance may vary from few KΩ to hundreds of MΩ and no chemical synthesis yields film of desired resistance with accuracy which has brought complexion in sensing with desired accuracy. Thus, the noble circuit designed is the ultimate way to eradicate this drawback of the ordinary sensor. Finally, designation of sensor can be summed up as:

(i) Measuring film resistance after fabrication R_x).

(ii) Choosing sensitivity (S).

(iii) Calculating Critical Resistance using selected sensitivity and Film Resistance as:

$$R_c = R_x - \frac{S \times R_x}{100} \quad \text{(Eq. 4)}$$

(iv) Choosing appropriate value of R_1:R_2, R_f and other circuital components and fabricating sensor.

Experimental Verification:

This was experimentally verified using alcohol (ethanol and methanol) vapors as reducing gas and ZnO as sensing material in the film. The value of the fabricated film resistance was more than 200 MΩ, ratio (R_1: R_2) was 1: 3, the value of feedback resistance was 560 KΩ and two eight pins chips (UA741CN) were used as amplifiers. Two LEDs (one red and another green) were fixed as shown in the circuit. 9 Volt battery was used as a source for two amplifier chips and another 3 Volt battery was conned in series with R_1, and R_2. The film was exposed to different concentrations of gas (alcohol vapors) and corresponding change was noted. The table below represents the experimental values.

Table no 4: Value of Input and Output Voltages of Circuit before and after exposure to alcohol vapors.

S.N.	Gas	Concentration (ppm)	Potential (V)			
			Before passing gas		After passing gas	
			Input	Output	Input	Output
1.	Ethanol	500	0.35	-4.15	6.27	2.56
		250	0.36	-4.15	5.11	2.28
		50	0.35	-4.14	4.12	2.13
2.	Methanol	500	0.36	-4.14	5.56	2.52
		250	0.34	-4.15	4.92	2.23
		50	0.36	-4.13	3.98	2.06

The table above clearly shows the switching of potential at output of circuit due to exposure of alcohol vapors. This confirms that the designed circuit senses alcohol vapor (reducing gas) using pristine zinc oxide thin film.

Response and Recovery:

Response and recovery time are another indispensable factor for determining whether or not a sensor is reliable. Here we have tabulated response and recovery time of our circuital sensor after exposure to different concentration of ethanol and methanol vapors.

Table no 5: Response and Recovery time of ZnO thin-film varying with concentration and types of alcohol.

S.N.	Alcohol	Concentration (ppm)	Response Time (s)	Recovery Time (s)
1.	Ethanol	500 250 50	2 4 6	60 28 10
2.	Methanol	500 250 50	2 5 8	80 35 15

The circuit remains in either normal state/zone (glowing Green) or in detection zone (glowing Red). When the target gas is passed, sooner the film resistance decreases and reaches the critical resistance, the circuit changes its state from normal and when the gas passes by, film resistance starts increasing again. As soon as it exceeds R_c, it changes its state back to normal. The time for which the circuit remains in either state while responding to different concentrations of Ethanol and Methanol vapors is shown below in Figure 12 :

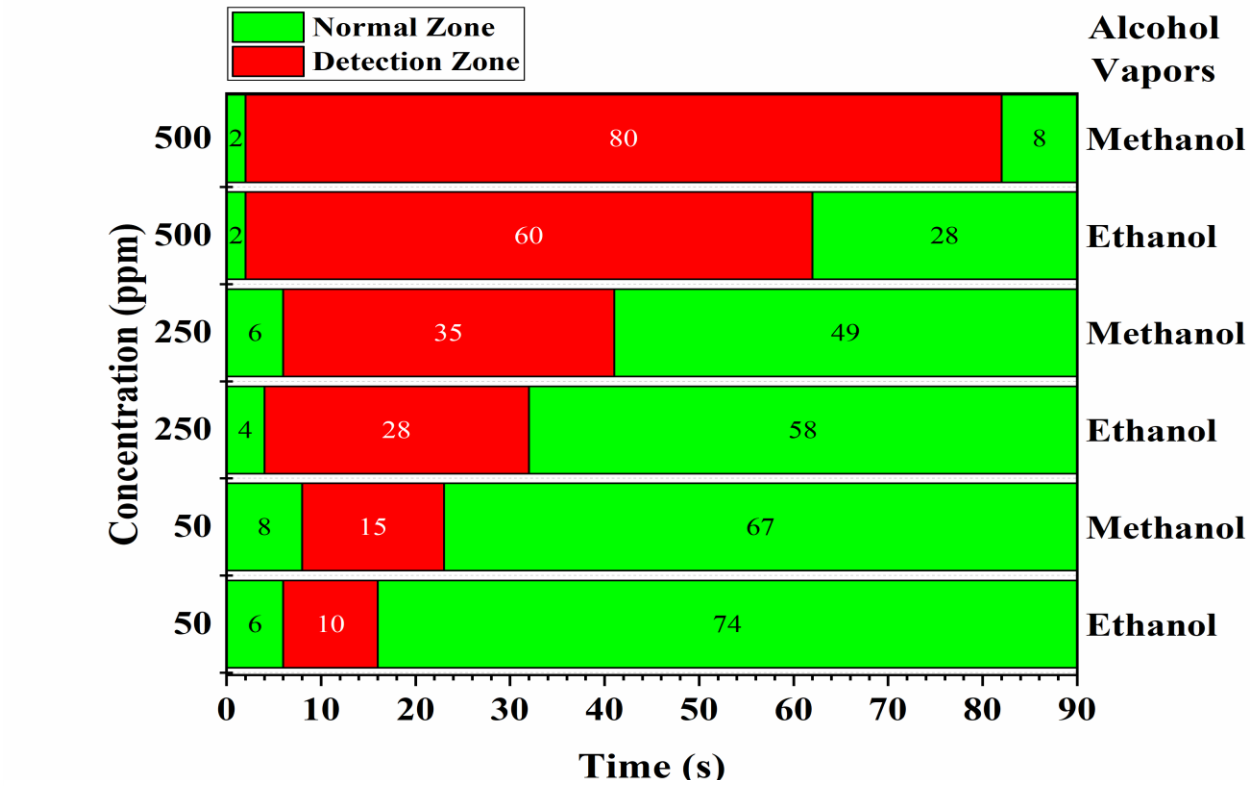

Figure 12: Time for which the circuit remains in either state in response to different concentration of alcohol vapors.

The figure above clearly depicts that higher the concentration, longer it stays in detection zone. Further, for same concentration, circuit responds faster to ethanol than methanol.

The vapors were passed simultaneously into the sensor setup and were free to escape at any time. The variation in film resistance in response to 50, 250 and 500 ppm of Ethanol and Methanol vapors were observed and are graphed as shown in Figure 13. The graph reflects that the resistance of the film while responding reducing gases decreases rapidly for few seconds then slows down and reaches its minimum value. The minimum value is attained when the

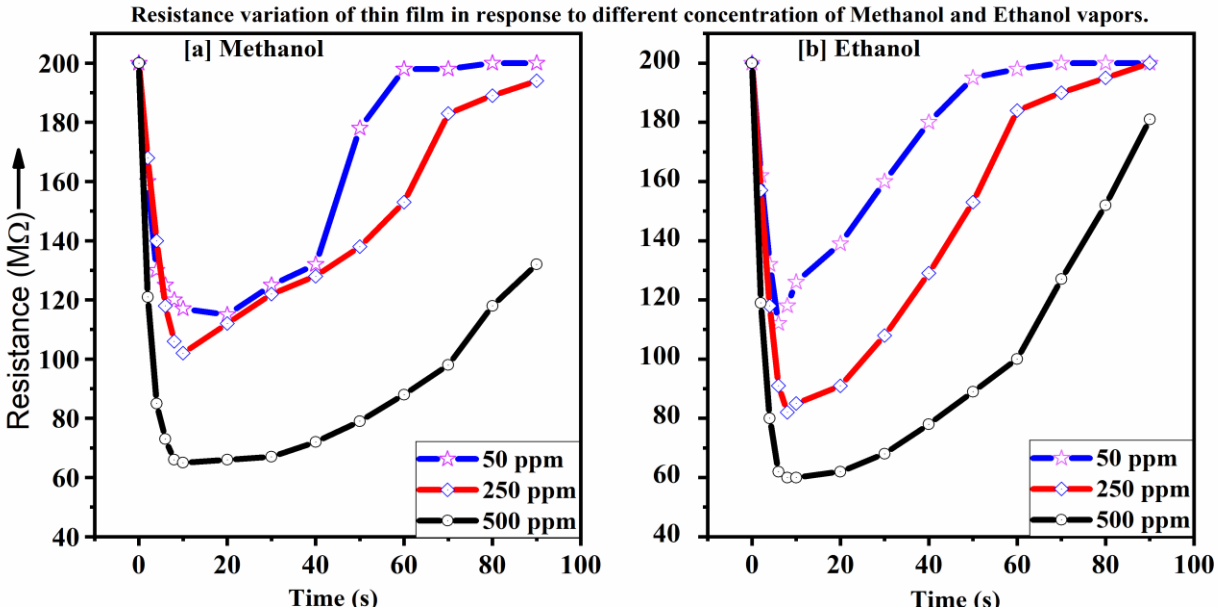

Figure 13: Variation of film resistance in response to various concentrations of Alcohol vapors.

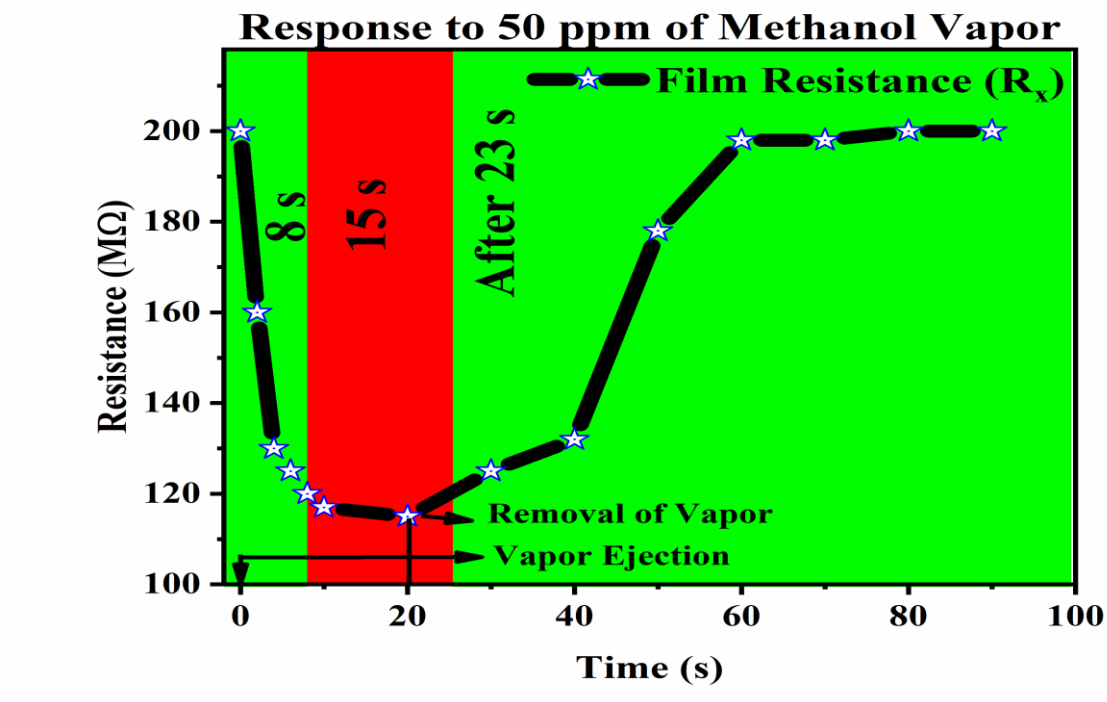

Figure 14: Film response to 50 ppm of Methanol Vapors.

target gases replace maximum number of reduced oxygen molecules in the grain boundary of film. As soon as the impact of the gas diminishes, the oxygen molecules in reduced form starts gathering at the grain boundary region and the film resistance starts increasing again. Its obvious that lower the concentration, less is the impact on film resistance.

Clearly, the experimental result shows that the film is sustainable and is very sensitive to reducing gases. The longevity of recovery time may be due to poor ventilation for gas outlet in our experimental setup.

IV. Conclusions

The novel circuit introduced for gas sensing approach can sense any reducing gases using zinc oxide thin film. After the fabrication of thin-film, film resistance will be known and analyzing table no 3, Figure 10 and Figure 11, we will be able to find the appropriate value of feedback resistor, the ratio of R_1 and R_2 to be used in the circuit for sensing particular gas within limited sensitivity range. Furthermore, the electrical components used are available in variable small size in the market, so we will be able to fabricate portable miniaturized sensing device or sensor of the desired size at low cost and consuming less energy, simply using zinc oxide thin film. Also, the circuit can be used for simple breathalyzer testing.

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