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Synthesis and Study of Electrical Properties of CuO thick films

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Abstract

The study of electrical properties of metal oxide semiconductors (MOS) is essential due to their widespread applications in various advanced technologies, particularly in sensors, optoelectronic devices, and energy-related systems. Metal oxide semiconductors such as CuO, ZnO, SnO_2, and other MOS exhibit unique electrical behaviors that are highly sensitive to external stimuli like temperature, gas environment, and light, making them ideal candidates for gas sensors, thermistors, and photodetectors. Understanding parameters like resistivity, temperature coefficient of resistance (TCR), and activation energy provides insights into their conduction mechanisms and allows for the optimization of their performance in specific applications. In the present study, copper oxide (CuO) nanoparticles were synthesized using the precipitation method. Thick films of CuO were subsequently developed on glass substrates via the screen printing technique. The primary objective of this work was to investigate the electrical properties of CuO thick films, which are of significant importance in the field of nanotechnology, particularly for metal oxide-based sensor applications. The electrical behavior of the fabricated films was analyzed using the half-bridge method. Key electrical parameters such as resistivity, temperature coefficient of resistance, and activation energy were systematically evaluated. The thickness of films was estimated using mass or weight difference method and thickness was found to be 67 µm. The CuO thick films exhibited a resistivity of 358593.5 Ω·m, a negative TCR of -0.00188°C^{-1}, and an activation energy of 0.2086 eV, indicating their potential for temperature-sensitive electronic applications.

Keywords: Metal Oxide, Precipitation, Electrical Properties, Resistivity, Activation Energy

1. Introduction:

In the field of nanotechnology, the electrical properties of metal oxide semiconductors play a pivotal role in the design and development of highly sensitive, miniaturized, and energy-efficient devices [1, 2]. At the nanoscale, these materials exhibit enhanced surface-to-volume ratios, quantum confinement effects, and unique charge transport mechanisms that significantly influence their electrical behavior. Parameters such as resistivity, carrier mobility, TCR, and activation energy become critical for optimizing performance in applications like nanosensors, nanoelectronics, and nanophotonic devices [3, 4]. The high sensitivity of metal oxide nanoparticles to slight changes in environmental conditions makes them ideal for gas sensing and biosensing platforms [5]. Moreover, the ability to tailor electrical properties through doping, nanostructuring, and surface modification allows for the customization of device functionalities at the atomic level. Thus, the study of electrical characteristics of metal oxide semiconductors are fundamental to advancing nanotechnology and developing next-generation smart materials and devices [5, 6].

Numerous studies have been conducted to explore their resistivity, temperature coefficient of resistance (TCR), and activation energy, which are critical for designing efficient gas sensors, thermoelectric materials, and transistors [7, 8]. For instance, ZnO and SnO_2 have demonstrated excellent n-type conductivity and sensitivity toward reducing gases, while CuO, a p-type semiconductor, shows promising behavior for temperature and humidity sensing applications. Researchers like Wang et al. (2012) and Singh et al. (2017) have reported the correlation between grain size, porosity, and electrical conduction in metal oxide thick films. These investigations highlight the importance of synthesis techniques, microstructure, and doping in tailoring electrical performance [9, 10]. Thus, continuous research on the electrical properties of metal oxide semiconductors is vital for developing next-generation electronic and sensor technologies.

CuO nanoparticles can be synthesized using a variety of methods, each offering control over particle size, morphology, crystallinity, and surface properties depending on the desired application [11]. Common methods include the precipitation method, which is simple and cost-effective, involving the reaction of a copper salt with a base to form a precipitate that is then calcined. The sol-gel method allows for better homogeneity and fine control over nanoparticle size by using metal alkoxides or salts in the presence of a gelling agent, followed by drying and calcination. Hydrothermal and solvothermal synthesis techniques involve heating an aqueous or solvent-based solution in a sealed autoclave, promoting the formation of highly crystalline and well-defined nanostructures under high pressure and temperature. Microwave-assisted synthesis provides rapid heating and uniform nucleation, resulting in smaller and more uniform particles in a shorter time [12, 13]. Green synthesis methods, which utilize plant extracts or biocompatible reducing agents, are gaining popularity due to their eco-friendly and non-toxic approach. Additionally, electrochemical and thermal decomposition methods are also employed for specific applications where control over purity and morphology is critical. The choice of synthesis method largely depends on factors such as cost, scalability, and the intended functional properties of the CuO nanoparticles [14, 15].

Screen printing is a versatile and widely used technique for fabricating thick films and patterned layers of functional materials on various substrates. In this process, a mesh screen usually made of polyester is used as a stencil, with specific areas blocked to define the desired pattern. A paste or ink containing the active material such as metal oxides, conductive polymers, or nanoparticles is applied onto the screen [16, 17]. A squeegee is then used to spread the paste across the screen, forcing it through the open areas of the mesh and onto the underlying substrate, typically glass, ceramic, or flexible polymer films. After printing, the coated substrate is dried and often subjected to thermal treatment such as sintering or calcination to enhance adhesion, remove organic binders, and improve the structural and functional properties of the film. Screen printing is particularly advantageous for its simplicity, low cost, scalability, and ability to produce uniform, repeatable layers with controlled thickness [17, 18]. It is commonly employed in the fabrication of sensors, solar cells, printed electronics, and thick film components in electronic devices.

In the present research work, CuO nanoparticles were synthesized using the precipitation method, and thick films were developed on glass substrates through the screen printing technique. The primary aim of this study is to investigate and elaborate on the electrical properties of CuO thick films.

2. Experimental work

All AR grade chemical were used to synthesis of CuO nanoparticles as well as for the preparation of CuO thick films.

2.1 Synthesis of CuO nanoparticles

CuO nanoparticles were synthesized using the precipitation method, a simple, cost-effective, and widely adopted technique for preparing metal oxide nanomaterials. In this method, an aqueous solution of copper nitrate ($Cu\ (NO_3)_2 \cdot 3H_2O$), was used as the precursor. Sodium hydroxide (NaOH) is used as precipitating agent. Initially, the 0.1 N solution of copper nitrate was prepared using double distilled water. After that, prepared solution of copper nitrate were kept on magnetic stirrer then NaOH was slowly added to the copper salt solution under constant magnetic stirring. This reaction led to the formation of a bluish precipitate of copper hydroxide, which upon continued stirring and controlled heating transformed into a black precipitate indicating the formation of copper oxide. The resulting precipitate was then filtered and thoroughly washed with ethanol to remove impurities and unreacted ions. After washing, the product was dried at moderate temperature and finally calcined at 400 °C temperature in the muffle furnace [19, 20]. This method yields fine CuO nanoparticles with controlled morphology and purity, suitable for further applications such as thick film fabrication and electrical property studies.

2.2 Preparation of CuO thick films

The preparation of CuO thick films was carried out using the screen printing technique, a widely used and efficient method for fabricating uniform and reproducible film layers on various substrates. In this process, a paste was first prepared by mixing the synthesized CuO nanoparticles with an organic binder such as ethyl cellulose (EC) and butyl carbitol acetate (BCA) to obtain a printable, viscous slurry or paste. To prepare CuO thick films, a thixotropic paste was formed using a 70:30 ratio of organic to inorganic materials, such as EC and BCA. This paste was carefully prepared by mixing CuO nanoparticles with the EC and BCA, creating a slurry with the desired viscosity and consistency. The organic material, EC, served as a binder that provided the necessary adhesion and flexibility, while the BCA helped to control the paste's rheological properties [21]. The prepared paste was then uniformly applied over a predefined mesh screen placed above a clean glass substrate. A squeegee was used to spread the paste across the screen, allowing the material to pass through the open areas of the mesh and deposit onto the substrate in the desired pattern. After printing, the coated substrate was dried under IR lamp to evaporate the solvent and ensure the adhesion of the film. Finally, the dried films were annealed at 400 °C temperature in the muffle furnace to remove the binder, enhance film density, and improve the electrical connectivity between particles [21, 22].

3. Result and discussion

The thickness of the prepared CuO thick films was estimated using the mass or weight difference method, which is a simple and effective technique for determining film thickness. In this method, the weight of the glass substrate before and after the deposition of the CuO film was measured using a high-precision balance. The mass difference, which corresponds to the amount of CuO material deposited on the substrate, was then used to calculate the film thickness [10, 21]. By knowing the density of the CuO material and the area of the film, the thickness was calculated using the relation between mass, density, and volume as shown in Eq. 1. After performing these calculations, the thickness of the CuO thick films was found to be 67 µm, indicating a relatively thick and robust film suitable for electrical and sensor applications.

$$Thickness(t) = \frac{\Delta W}{\rho A} \qquad \text{(Eq. 1)}$$

Where,

ΔW is Mass difference between the substrate before and after film deposition,ρ = Density of the material (in g/cm^3 or kg/m^3), A = Area of the film on the substrate

The electrical properties such as resistivity, temperature coefficient of resistance, and activation energy were calculated using Eqs. 2, 3 and 4 respectively.

$$\rho = \left(\frac{R \times b \times t}{l}\right)\Omega - m \qquad \text{(Eq. 2)}$$

Where,

ρ = Resistivity of prepared film, R = resistance at normal temperature, b = breadth of film,
t = thickness of the film, *l* = length of the film.

$$TCR = \frac{1}{R_o}\left(\frac{\Delta R}{\Delta T}\right) /^{o}C \qquad \text{(Eq. 3)}$$

Where,

ΔR = change in resistance between temperature T_1 and T_2,ΔT = temperature difference between T_1 and T_2 and R_o = room temperature resistance of the film.

$$\Delta E = Ae^{-Ea/kBT} \quad eV \qquad \text{(Eq. 4)}$$

Where,

ΔE = Activation energy, T = Temperature in Kelvin and A = Arrhenius prefactor.

Figure 1 illustrates the variation of electrical resistance of CuO thick films with respect to temperature, ranging from approximately 300 K to 620 K. The plot clearly shows a negative temperature coefficient of resistance (NTCR) behavior, which is typical of semiconducting materials. As the temperature increases, the resistance of the CuO thick film decreases exponentially. This trend confirms the thermally activated conduction mechanism in CuO, where increasing thermal energy excites more charge carriers (electrons or holes), thereby enhancing electrical conductivity and reducing resistance [21, 22]. In the lower temperature region (300–400 K), the resistance drops sharply, indicating that the charge carrier activation is more dominant in this range. Beyond approximately 450 K, the resistance continues to decrease but at a slower rate, eventually stabilizing between 550 K and 620 K. This behavior suggests that most of the accessible charge carriers are already activated at higher temperatures, and the conduction approaches a saturation region. Such thermal behavior is important in gas sensing and electronic device applications, as it reflects the film’s potential to respond to temperature changes and possibly external stimuli like gases. The smooth and continuous decrease in resistance further confirms the good quality and uniformity of the CuO thick films prepared via the screen printing technique [21, 23].

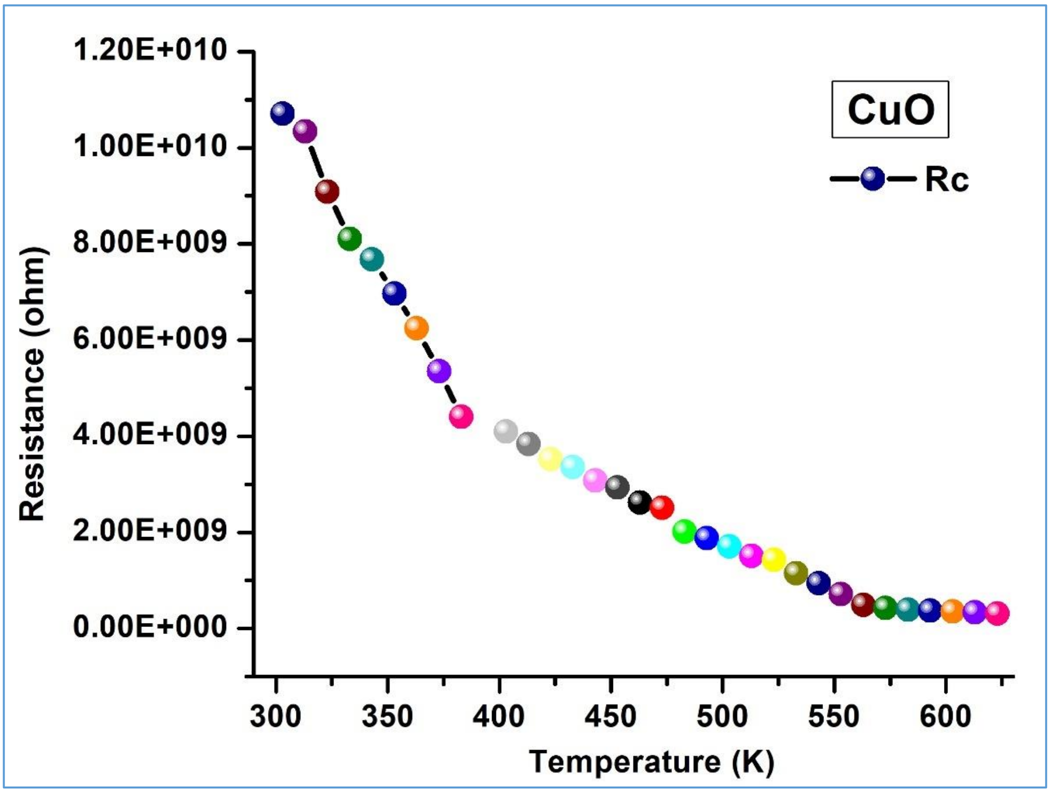

Figure 1: Temperature versus resistance plot of CuO thick films

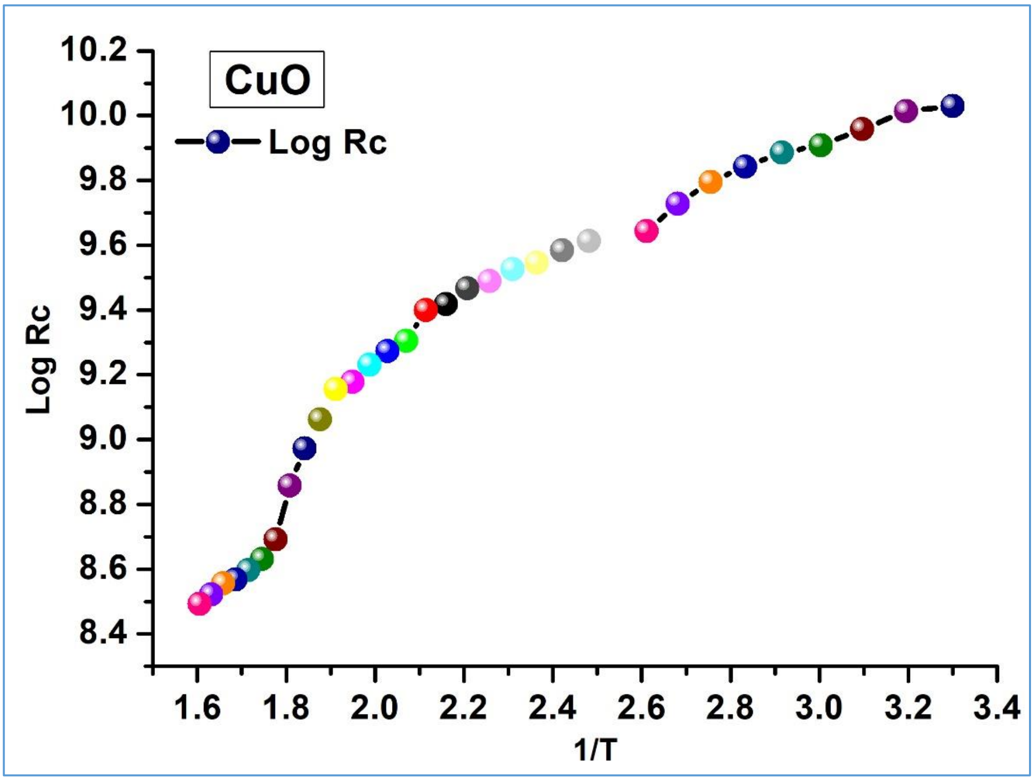

Figure 2: Log Rc versus 1/T plot of CuO thick films

Figure 2 presents the plot of logarithmic resistance (Log Rc) versus the reciprocal of temperature (1/T) for CuO thick films, which is a classical approach to analyze the thermal activation behavior of semiconducting materials. In this graph, the x-axis represents 1/T, and the y-axis shows log Rc. The positive slope observed in the graph confirms that the resistance increases as the temperature decreases, consistent with the negative temperature coefficient of resistance (NTCR) behavior typical of CuO, a p-type semiconductor [10, 24].The linear portion of the graph allows for the calculation of the activation energy (E_a), which provides insight into the energy barrier that charge carriers must overcome for conduction [24, 25]. In this study, the activation energy calculated from the slope was found to be 0.2086 eV, indicating that the conduction is thermally activated and consistent with intrinsic semiconductor behavior at higher temperatures [25, 26].This plot further validates the semiconducting nature of the CuO thick films and is crucial for evaluating their suitability in temperature-sensitive and gas sensing applications [27].

Table-1: Electrical outcomes of pure CuO thick films

Thick Film	**Thickness (μm)**	**Resistivity (Ω-m)**	**TCR (/ºC)**	**Activation energy (eV)**
CuO	67	358593.5	-0.00188	0.2086

Conclusions

The CuO nanoparticles were successfully synthesized using the precipitation method and employed to fabricate thick films on glass substrates via the screen printing technique. A thixotropic paste was prepared using a 70:30 ratio of organic (ethyl cellulose) and inorganic (butyl carbitol acetate) binders to ensure uniform film deposition. The thickness of the films was estimated using the weight difference method and found to be approximately 67 µm. The electrical properties of the CuO thick films were systematically investigated using the half-bridge method. The temperature-dependent resistance measurements revealed that the films exhibit typical semiconducting behavior with a negative temperature coefficient of resistance (NTCR). The resistance decreased exponentially with an increase in temperature, indicating thermally activated conduction. The log Rc versus 1/T plot confirmed this behavior and enabled the calculation of activation energy, which was found to be 0.2086 eV. Additionally, the resistivity and temperature coefficient of resistance (TCR) were calculated as 358593.5 Ω·m and -0.00188 $°C^{-1}$, respectively. These results validate that the CuO thick films possess suitable electrical characteristics for potential applications in temperature sensors and gas sensing devices within the field of nanotechnology.

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References

1. Chavali, M.S. and Nikolova, M.P., 2019. Metal oxide nanoparticles and their applications in nanotechnology. *SN applied sciences*, *1*(6), p.607.
2. Nunes, D., Pimentel, A., Gonçalves, A., Pereira, S., Branquinho, R., Barquinha, P., Fortunato, E. and Martins, R., 2019. Metal oxide nanostructures for sensor applications. *Semiconductor Science and Technology*, *34*(4), p.043001.

3. Abu-Dief, A.M., 2020. Development of metal oxide nanoparticles as semiconductors. *Journal of Nanotechnology and Nanomaterials*, *1*(1), pp.5-10.
4. Ouyang, W., Teng, F., He, J.H. and Fang, X., 2019. Enhancing the photoelectric performance of photodetectors based on metal oxide semiconductors by charge-carrier engineering. *Advanced Functional Materials*, *29*(9), p.1807672.
5. Sun, Y.F., Liu, S.B., Meng, F.L., Liu, J.Y., Jin, Z., Kong, L.T. and Liu, J.H., 2012. Metal oxide nanostructures and their gas sensing properties: a review. *Sensors*, *12*(3), pp.2610-2631.
6. Comini, E., Baratto, C., Concina, I., Faglia, G., Falasconi, M., Ferroni, M., Galstyan, V., Gobbi, E., Ponzoni, A., Vomiero, A. and Zappa, D., 2013. Metal oxide nanoscience and nanotechnology for chemical sensors. *Sensors and Actuators B: Chemical*, *179*, pp.3-20.
7. Feteira, A., 2009. Negative temperature coefficient resistance (NTCR) ceramic thermistors: an industrial perspective. *Journal of the American Ceramic Society*, *92*(5), pp.967-983.
8. Williams, D.E., 1999. Semiconducting oxides as gas-sensitive resistors. *Sensors and Actuators B: Chemical*, *57*(1-3), pp.1-16.
9. Patil, S.J., Patil, A.V., Dighavkar, C.G., Thakare, K.S., Borase, R.Y., Nandre, S.J., Deshpande, N.G. and Ahire, R.R., 2015. Semiconductor metal oxide compounds based gas sensors: A literature review. *Frontiers of Materials Science*, *9*, pp.14-37.Parida, K., Bark, H. and Lee, P.S., 2021. Emerging thermal technology enabled augmented reality. *Advanced Functional Materials*, *31*(39), p.2007952.
10. Tupe, U.J., Zambare, M.S., Patil, A.V. and Koli, P.B., 2020. The binary oxide NiO-CuO nanocomposite based thick film sensor for the acute detection of Hydrogen Sulphide gas vapours. *Material Science Research India*, *17*(3), pp.260-269.
11. El-Trass, A., ElShamy, H., El-Mehasseb, I. and El-Kemary, M., 2012. CuO nanoparticles: synthesis, characterization, optical properties and interaction with amino acids. *Applied Surface Science*, *258*(7), pp.2997-3001.
12. Oruç, Ç. and Altındal, A., 2017. Structural and dielectric properties of CuO nanoparticles. *Ceramics international*, *43*(14), pp.10708-10714.
13. Phiwdang, K., Suphankij, S., Mekprasart, W. and Pecharapa, W., 2013. Synthesis of CuO nanoparticles by precipitation method using different precursors. *Energy procedia*, *34*, pp.740-745.
14. Sagadevan, S. and Priya, M., 2015. Electrical properties of copper oxide nanoparticles. *Journal of Nano Research*, *30*, pp.1-8.
15. Paquet, C., James, R., Kell, A.J., Mozenson, O., Ferrigno, J., Lafrenière, S. and Malenfant, P.R., 2014. Photosintering and electrical performance of CuO nanoparticle inks. *Organic Electronics*, *15*(8), pp.1836-1842.
16. Pan, J., Tonkay, G.L. and Quintero, A., 1999. Screen printing process design of experiments for fine line printing of thick film ceramic substrates. *Journal of Electronics Manufacturing*, *9*(03), pp.203-213.
17. Ménil, F., Debéda, H. and Lucat, C., 2005. Screen-printed thick-films: from materials to functional devices. *Journal of the European ceramic society*, *25*(12), pp.2105-2113.
18. VijatovićPetrović, M., Bobić, J., Stojanović, B.D. and Malič, B., 2010. Barium titanate thick films prepared by screen printing technique. *Processing and Application of Ceramics*, *4*(2), pp.53-58.

19. Luna, I.Z., Hilary, L.N., Chowdhury, A.S., Gafur, M.A., Khan, N. and Khan, R.A., 2015. Preparation and characterization of copper oxide nanoparticles synthesized via chemical precipitation method. *Open Access Library Journal*, *2*(3), pp.1-8.
20. Sagadevan, S., Pal, K. and Chowdhury, Z.Z., 2017. Fabrication of CuO nanoparticles for structural, optical and dielectric analysis using chemical precipitation method. *Journal of Materials Science: Materials in Electronics*, *28*, pp.12591-12597.
21. Patil, A., Dighavkar, C., Borse, R., Patil, S. and Khadayate, R., 2012. Effect of Cr2O3 by doping and dipping on gas sensing characteristics of ZnO thick films. *Journal of Electron Devices*, *15*, pp.1274-1281.
22. Patil, A., Tupe, U.J. and Patil, A.V., 2021. Reduced graphene oxide screen printed thick film as NO2 gas sensor at low temperature. *Advanced Materials Research*, *1167*, pp.43-55.
23. Alghamdi, H.A., 2022. Structural, morphological, optical, and electrical characteristics of polyethylene oxide/chitosan-copper oxide nanoparticles for optoelectronic applications. *Optical Materials*, *134*, p.113101.
24. Koli, P.B., Kapadnis, K.H., Deshpande, U.G., Tupe, U.J., Shinde, S.G. and Ingale, R.S., 2021. Fabrication of thin film sensors by spin coating using sol-gel LaCrO3 Perovskite material modified with transition metals for sensing environmental pollutants, greenhouse gases and relative humidity. *Environmental Challenges*, *3*, p.100043.
25. Bagul, V.R., Bhagure, G.R., Ahire, S.A., Patil, A.V., Adole, V.A. and Koli, P.B., 2021. Fabrication, characterization and exploration of cobalt (II) ion doped, modified zinc oxide thick film sensor for gas sensing characteristics of some pernicious gases. *Journal of the Indian Chemical Society*, *98*(11), p.100187.
26. Ahire, S.A., Koli, P.B., Patil, A.V., Jagdale, B.S., Bachhav, A.A. and Pawar, T.B., 2021. Designing of screen-printed stannous oxide (SnO2) thick film sensors modified by cobalt and nitrogen elements for sensing some toxic gases and volatile organic compounds. *Current Research in Green and Sustainable Chemistry*, *4*, p.100213.
27. Patil, A.V., Handge, S.B., Dighavkar, C.G., Shelar, R.N. and Patil, D.R., 2015. Ethanol vapour sensing property of Nitrogen doped ZnO fabricated by Spray pyrolysis. *Advanced Materials Research*, *1110*, pp.231-234.