Study of Electrical and Gas Sensing Properties of Cadmium Sulfide Thick Films

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Abstract
The study of electrical and gas-sensing properties of Cadmium Sulfide (CdS) thick films is crucial for understanding their potential applications in gas sensing technologies. CdS is a wide bandgap semiconductor material that exhibits a unique property called photo-conductivity, which means its electrical conductivity changes in response to light or gas exposure. This property makes CdS a promising candidate for gas sensing applications. In the present research work author investigated the electrical and gas sensing properties of CdS thick films developed by screen printing method. The electrical and gas sensing properties were investigated using static electric and gas sensing system. The resistivity of the films was studied using half bridge method. The resistivity, TCR and activation energy of films were found to be 509575 Ω.m, -0.00233 /°C and 0.1067 eV respectively. A film shows maximum gas response to the NO_2 gas at operating temperature 120 °C. The maximum sensitivity was found to be 73.68 %. The films exhibit quick response and recovery time.

Keywords: Thick films, Cadmium Sulfide, gas sensors, air pollution, photoconductive.

1. Introduction:

Air pollution refers to the presence of contaminants and excessive amounts of certain substances in the Earth's atmosphere. These contaminants can originate from both natural sources, such as volcanic eruptions and wildfires, and human activities, including industrial processes, transportation, and energy production [1, 2]. Air pollution can have severe consequences on public health, climate change, and ecosystems. Some major components of air pollution include particulate matter (PM), ground-level ozone, nitrogen oxides (NOx), sulfur dioxide (SO2), carbon monoxide (CO), and volatile organic compounds (VOCs). These pollutants can lead to respiratory and cardiovascular diseases, premature death, and other health issues when inhaled by humans [1-3]. Nitrogen dioxide (NO_2) is a significant air pollutant and a major component of photochemical smog. It is primarily produced by combustion processes, such as those occurring in vehicles, power plants, and industrial facilities. The presence of NO_2 in the atmosphere can have various detrimental effects on human health, the environment, and materials [4, 5]. Prolonged exposure to NO_2 is lead to respiratory problems, aggravate existing respiratory and cardiovascular diseases, and cause premature death. It can irritate the airways, lungs, and eyes, leading to symptoms like coughing, wheezing, and shortness of breath. Children, the elderly, and people with pre-existing health conditions are particularly vulnerable to the effects of NO_2 [5, 6].

Metal sulfides, being a class of semiconductor materials, have been extensively researched and utilized in the development of gas sensors [7]. These sensors function based on the interaction between the metal sulfide material and the target gas molecules. When gas molecules adsorb onto the metal sulfide surface, it causes a change in the material's electrical properties, such as resistance or capacitance. This change can then be measured and translated into a detectable signal, allowing for the identification and quantification of the gas present. Metal sulfide-based gas sensors have been applied to detect various gases, including oxidizing and reducing gases, offering potential for use in air quality monitoring, industrial safety, and environmental applications [7, 8]. Cadmium Sulfide (CdS) is a chemical compound commonly used in various applications due to its unique properties. It is a semiconductor material with a wide bandgap, which makes it suitable for photoconductive and photovoltaic devices [9]. Additionally, CdS has been employed in the production of red light-emitting diodes (LEDs) and as a pigment in the past, although its use as a pigment has been largely replaced by safer alternatives due to health and environmental concerns [9- 11].

Screen printing is a widely used technique for depositing thick films on various substrates, including those employed in gas sensor fabrication [12]. This method offers several advantages, such as cost-effectiveness, high throughput, and the ability to produce complex patterns. When it comes to creating thick films for gas sensors, screen printing can be particularly useful for depositing conductive inks or pastes that respond to specific gas concentrations [13, 14]. The major aim of the current research work is to study the electrical and gas sensing properties of CdS thick films developed by screen printing method.

2. Materials and methods

The commercially avilable CdS nanopowder purchased from sigma enterprises, Nashik was used for the development of thick films. The films were developed on glass substrate by screen printing method. The inorganic and organic materials 70:30% ratio was used to develop pure CdS thick films [15]. The inorganic material consists of CdS nanopowder while organic materials including butyl carbitol acetate and ethyl cellulose. Fig. 1 reveals the schematic diagram of development of thick films using screen printing method.

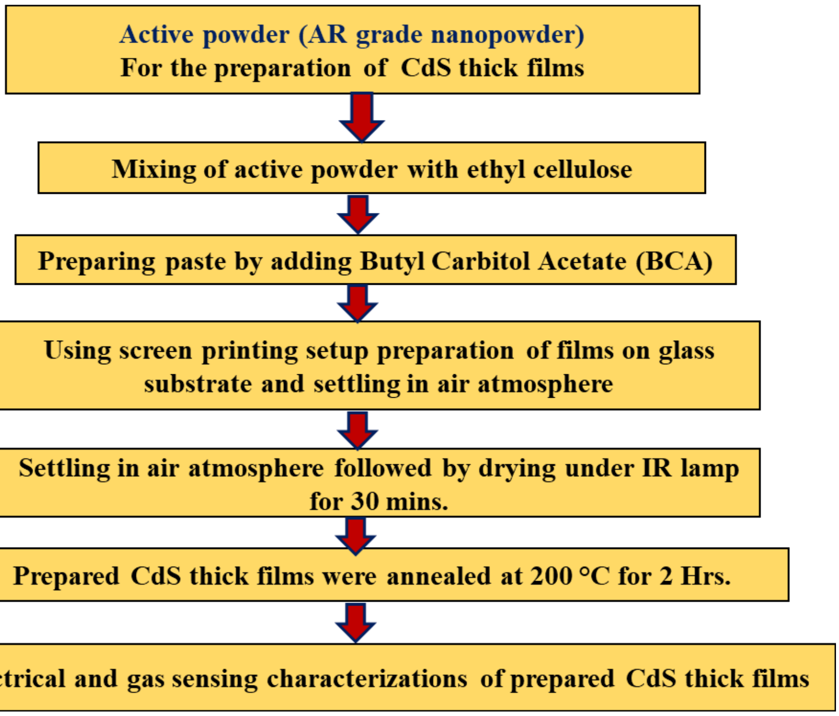

Figure 1: Steps of development of CdS thick films using screen printing method

3. Result and discussion

The half-bridge circuit configuration is a widely used method for electrical characterization, particularly for measuring resistance, inductance, and capacitance in various electronic components and circuits. It offers several advantages, such as simplicity, high accuracy, and the ability to handle high voltages and currents. The schematic diagram of half-bridge circuit configuration is shown in Fig. 2 [15, 16]. Resistivity of thick films refers to the measure of a material's resistance to the flow of electric current when formed into a film with a significant thickness. The resistivity of thick films is an essential parameter for various applications, such as conductive inks, coatings, and printed electronic devices, including gas sensors, flexible displays, and RFID tags. Resistivity (ρ) is a fundamental property of a material and is defined as the resistance (R) per unit length (L) of a conductor with a uniform cross-sectional area (A). The relationship between these parameters can be expressed by the formula (Eq. 1).

$$\rho = R \times A / L \qquad (1)$$

Where, ρ= Resistivity, R= resistance at room temperature, L= length and A= area of film

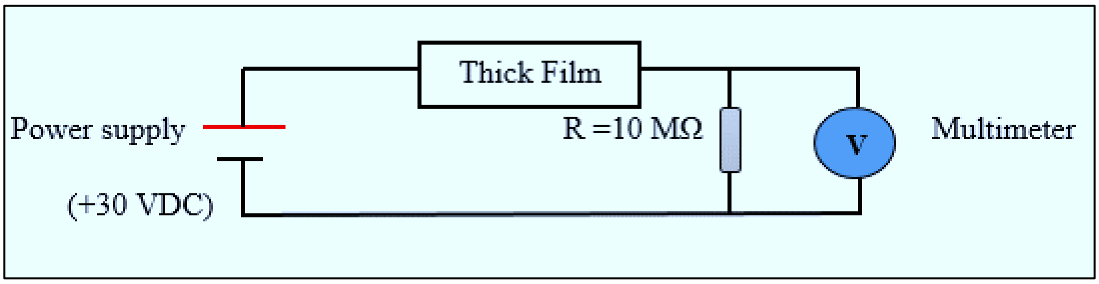

Figure 2: Schematic of a half-bridge circuit

Fig. 3 shows the resistance verses temperature plot of CdS thick films. It has been observed that from Fig. 3 the resistance of the films is decline as ambient temperature is increased [17, 18]. This type of nature of graph indicating semiconducting nature of the film. The resistance of the film decreased due to increase the mobility of carrier concentration as heat increases.

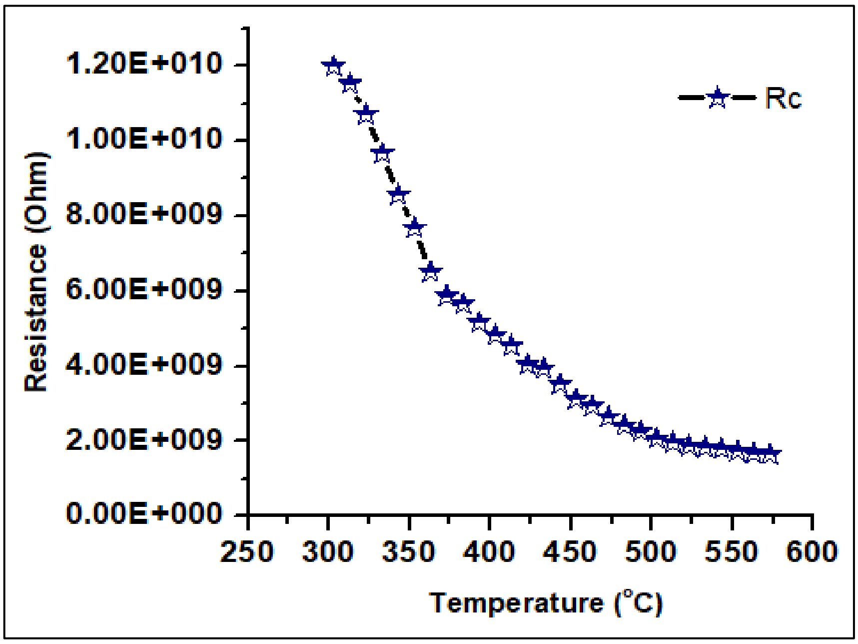

Figure 3: Resistance verses temperature plot of CdS thick films

Activation energy of thick films is a crucial parameter in gas sensing applications, as it significantly affects the performance and reliability of the sensors [18, 19]. The activation energy refers to the minimum amount of energy required for a chemical reaction to occur. In the context of gas sensing, it is crucial for understanding the interaction between the thick film and the target gas molecules. It is crucial for gas sensing applications, as it influences the sensitivity, selectivity, response time, stability, temperature dependence, and data interpretation of the gas sensor [20, 21]. By optimizing the activation energy and understanding its impact on the gas sensing process, one can enhance the overall effectiveness of gas sensors. The Arrhenius equation is a mathematical model that relates the rate of a reaction to the temperature at which it occurs. The activation energy is calculated by measuring the rate constant (k) at different temperatures (T) and using the known pre-exponential factor (A) for a specific reaction. The Arrhenius equation is presented in Eq. 2. $\Delta E = \frac{\log R}{\log Ro} \times KT$

(2)

Where, ΔE = Activation energy, R = Resistance at elevated temperature, R_0 = Resistance at room temperature. Fig. 4 reveals the plot of log Rc vs. 1/T of CdS thick films. By employing Arrhenius equation (Eq.2) the activation energy was estimated. The activation energy for CdS thick films was found to be 0.14580 eV and 0.10679 eV at higher and lower temperature regions respectively.

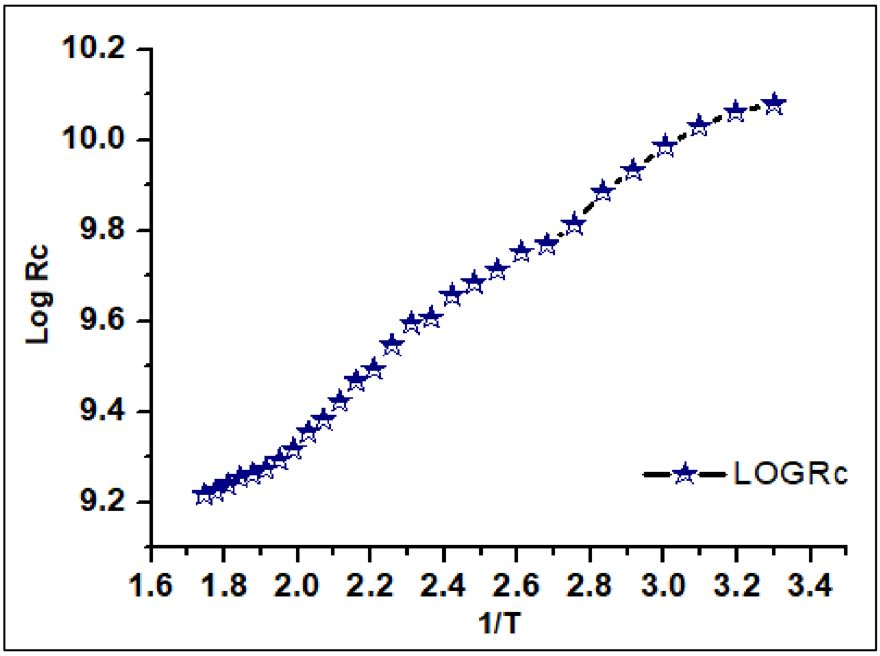

Figure 4: Arrhenius plot of log Rc vs. 1/T of CdS thick films

The Temperature Coefficient of Resistance (TCR) of thick films is indeed important for gas sensing applications. TCR is a measure of how much a material's electrical resistance changes with a change in temperature [15, 21]. In the context of gas sensing, it plays a significant role in determining the performance and reliability of the gas sensor. The TCR of the thick film material influences the sensitivity of the gas sensor. As the temperature of the thick film changes, its resistance also varies, which in turn affects the electrical signal generated by the sensor. A higher TCR can lead to a more significant change in resistance with temperature, potentially increasing the sensitivity of the gas sensor towards the target gas. The TCR of films was estimated using Eq. 3 and it was found to be -0.00233 /°C.

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

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

Gas sensor sensitivity refers to the ability of a gas sensor to detect and respond to changes in the concentration of a particular gas. It is affected by factors such as relative humidity, temperature, response time, and time of exposure to the gas. The sensitivity of the films was estimated using Eq. 4. sensitivity (S%) is defined as ratio of change in resistance in air to the change in resistance in presence of gas for reducing gases and for oxidizing ratio of change in resistance in air to the change in resistance in presence of gas [15, 16].

$$\text{Sensitivity (\%)} = Ra/Rg \text{ or } Rg/Ra \times 100 \qquad (4)$$

Where, Ra stands for the resistance of gas sensors in the reference gas (usually the air) and Rg stands for the resistance in the reference gas containing target gases.

Gas sensors can have different levels of sensitivity depending on the type of sensor and the gas being detected [19]. Fig. 5 reveals the sensitivity versus temperature plot of CdS thick films. From Fig. 5, the CdS thick films shows more sensitivity to NO_2 gas compare to other selected. The maximum sensitivity was found to be 73.68% at operating temperature 120 °C and the gas concentration was 1000 ppm. The CdS thick film sensors work by detecting the presence and concentration of various gases in the air using physical or chemical reactions to convert the concentration of gases into electrical signals [18, 21]. The gas molecules react with the sensing material in the sensor, causing a change in its electrical conductivity or potential, which is then measured and converted into a signal [19, 20].

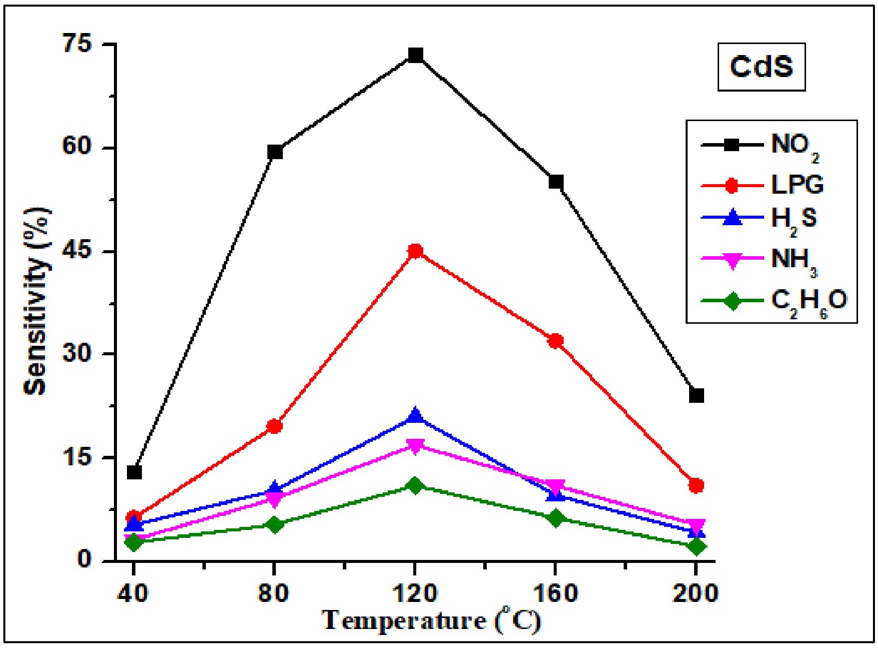

Figure 5: Sensitivity versus temperature plot of CdS thick films

Selectivity in gas sensors refers to the ability of a sensor to specifically recognize and respond to a single target gas species without significant responses to other interfering substances present in the environment [21, 21]. Enhancing selectivity is essential for accurate measurements and reliable operation of gas sensors, especially in complex atmospheres containing multiple gases. Fig. 6 shows the selectivity plot of CdS thick films to selected gases.

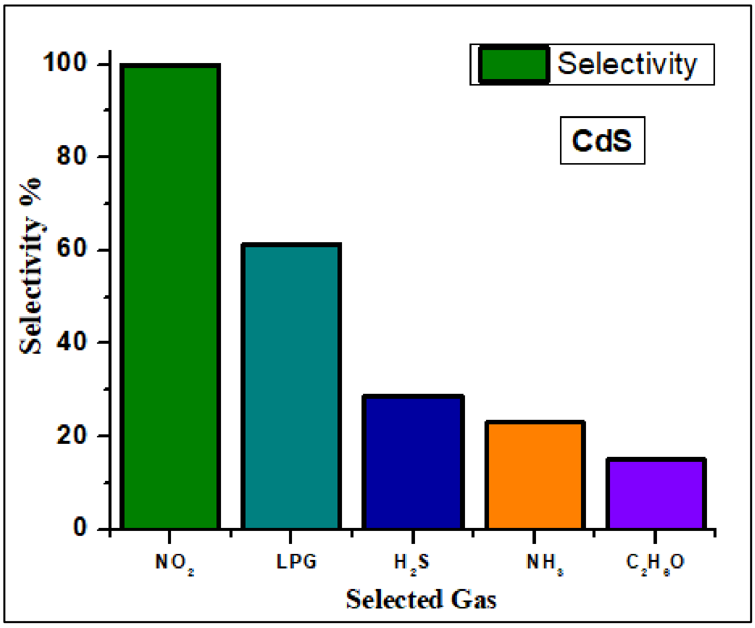

Figure 6: Selectivity graph of CdS thick films

The response time of a gas sensor is the time it takes for the sensor to register a change in the presence of a gas, typically from 10% to 90% of the overall signal change. It is an important parameter as it determines how quickly the sensor can detect the presence of a gas. The recovery time, on the other hand, is the time it takes for the sensor to return to its initial state after being exposed to a gas. This is crucial for ensuring that the sensor is ready to detect a new gas concentration [19, 20]. Both response and recovery times are essential for the effective operation of gas sensors, with faster times being generally more desirable. The response and recovery times can be influenced by various factors such as the sensor material, temperature, and experimental setup [20, 21]. Fig. 7 display the response and recovery time plot of CdS thick films to NO_2 gas. The response and recovery time was found to be 12 and 65 seconds respectively to the CdS films.

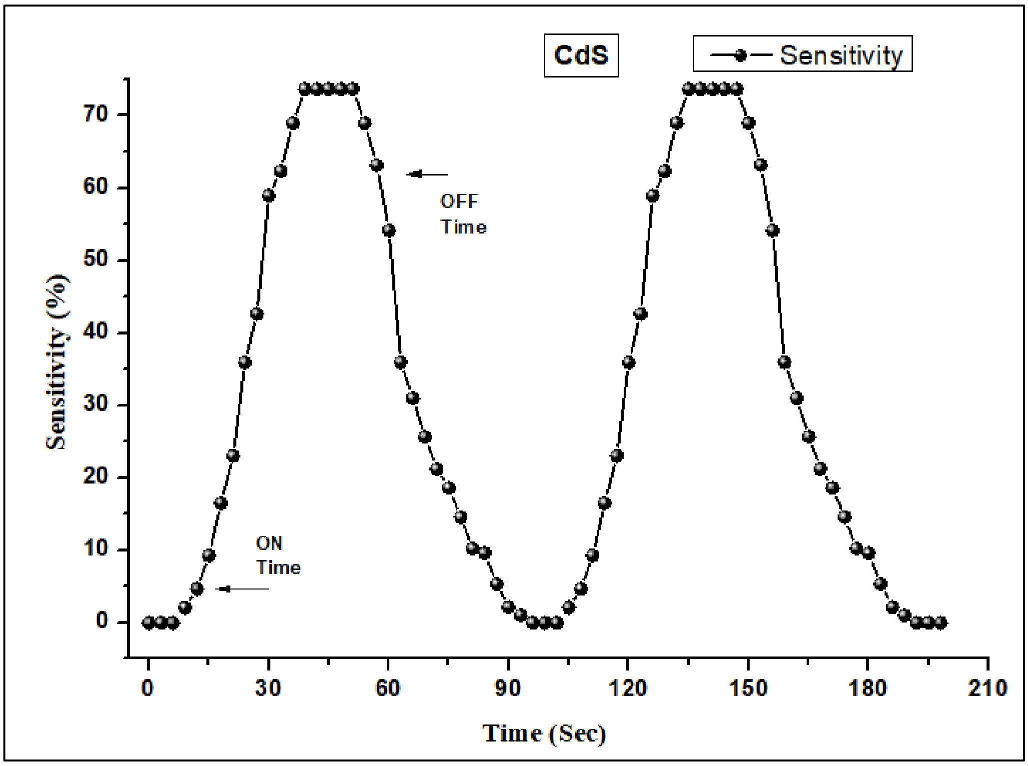

Figure 7: Response and recovery time plot of CdS thick films to NO_2 gas

The Gas sensing mechanism of CdS thick films to NO_2 gas involved chemosensor principle [21]. When NO_2 molecules adsorb onto the CdS surface, capturing free electrons from the conduction band (CB). As NO_2 adsorbs onto the CdS surface, the number of free electrons in the CB decreases, leading to an increase in resistance and change in resistance is recorded as sensitivity or gas response of the film [22, 23].

Conclusions and future scope:

The thick film gas sensing applications span across various industries and sectors, playing a vital role in maintaining environmental quality, ensuring industrial and domestic safety, optimizing processes, and improving overall efficiency. The versatility and cost-effectiveness of thick film gas sensors make them an indispensable tool for gas detection and monitoring. The CdS thick films were successfully prepared on glass substrate by using screen-printing technique. Prepared films shows semiconducting nature with negative TCR. Films shows maximum sensitivity to NO_2 gas at operating temperature 120 °C. Prepared films could be used of the fabrication of NO_2 gas sensor.

Acknowledgment
Author thanks to the Principal of M. G. V's M. S. G. Arts, Science and Commerce College, Malegaon, Malegaon camp, Dist- Nashik, India, for providing necessary support for the present research work.

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