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Gas Sensing Study of Strontium Oxide Thick Films Fabricated by Screen Printing Method

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Abstract:
In the present study, strontium oxide (SrO) thick films were successfully fabricated using the screen printing technique and systematically investigated for their gas sensing performance toward selected gases like LPG, CO_2, H_2S, and methanol. The structural simplicity, low cost and scalability of the screen printing method make it suitable for the development of practical gas sensor devices. The sensing characteristics were evaluated in terms of sensitivity, selectivity, gas concentration (ppm) variation, and response /recovery time. The SrO thick films exhibited a pronounced and selective response toward LPG, achieving a maximum sensitivity of 78.96% at an optimal operating temperature of 150 °C for a gas concentration of 500 ppm. Comparative studies revealed significantly lower responses toward CO_2, H_2S, and methanol, confirming excellent selectivity of the SrO films for LPG detection. The sensor demonstrated fast response and recovery characteristics with response and recovery times of 16 s and 53 s, respectively, indicating efficient adsorption–desorption kinetics on the film surface. These results highlight the potential of SrO thick films as promising candidates for low-cost, sensitive, and selective LPG sensors operating at moderate temperatures.

Keywords: SrO thick films; screen printing technique; LPG sensor; gas sensitivity; selectivity; chemoresistive gas sensing.

1. Introduction:

The rapid growth of industrialization, urbanization, and the extensive use of fossil fuels have resulted in a significant increase in the emission of flammable and toxic gases into the environment. Among these, liquefied petroleum gas (LPG), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and volatile organic compounds such as methanol are of major concern due to their widespread domestic and industrial usage and their associated safety and environmental hazards [1, 2]. LPG is extensively used as a domestic and industrial fuel; however, its leakage can lead to severe fire hazards and explosions, necessitating the development of reliable and sensitive gas detection systems. CO_2 is a major greenhouse gas contributing to global warming, while H_2S is highly toxic even at low concentrations and methanol vapors pose serious health risks upon prolonged exposure. Consequently, the development of low-cost, sensitive, selective, and fast-response gas sensors for real-time monitoring of these gases has become an important area of research in materials science and sensor technology [2-5]. Semiconducting metal oxide-based gas sensors have attracted considerable attention owing to their simple design, robustness, low fabrication cost, and compatibility with miniaturized electronic devices. The gas sensing mechanism in these materials is

primarily governed by changes in electrical resistance resulting from surface interactions between the target gas molecules and chemisorbed oxygen species on the oxide surface. When exposed to air, oxygen molecules adsorb on the surface of metal oxides and extract electrons from the conduction band, forming ionized oxygen species. Upon exposure to reducing or oxidizing gases, these adsorbed species participate in surface reactions, leading to measurable changes in resistance [5-7]. The sensing performance of metal oxide semiconductors is strongly influenced by factors such as crystal structure, grain size, surface morphology, porosity, defect density, operating temperature, and the nature of the target gas. A wide range of metal oxides, including SnO_2, ZnO, WO_3, TiO_2, NiO, and MgO, have been extensively investigated for gas sensing applications. While many of these materials demonstrate good sensitivity, challenges such as high operating temperature, poor selectivity, long-term instability, and slow response–recovery behavior still limit their practical deployment[8, 9]. In recent years, alkaline earth metal oxides have emerged as promising alternatives due to their strong basic nature, high chemical stability, and favorable surface reactivity toward acidic and hydrocarbon gases. Among them, strontium oxide (SrO) has gained attention because of its high surface basicity, wide band gap, thermal stability, and strong affinity toward hydrocarbon molecules, making it a potential candidate for gas sensing applications [10, 11]. Strontium oxide is an n-type wide band gap semiconductor with a rock-salt crystal structure, similar to other alkaline earth metal oxides. Its basic surface sites promote enhanced adsorption of hydrocarbon gases such as LPG, leading to improved sensing response. It exhibits good resistance to chemical poisoning and structural degradation at elevated temperatures, which is essential for long-term sensor operation. Previous studies have reported that SrO-based materials and SrO-doped composites show improved sensitivity and selectivity toward reducing gases, attributed to enhanced surface reaction kinetics and increased density of active adsorption sites [12, 13. However, systematic studies focusing exclusively on SrO thick films and their comparative sensing response toward multiple target gases remain limited. The fabrication technique plays a crucial role in determining the microstructural and sensing properties of gas sensor materials. Among various deposition methods such as sol–gel spin coating, spray pyrolysis, chemical vapor deposition, and pulsed laser deposition, the screen printing technique is widely recognized for thick film sensor fabrication due to its simplicity, cost-effectiveness, reproducibility, and suitability for large-area and mass production. Screen-printed thick films generally exhibit high porosity, large surface area, and interconnected grain networks, which are highly desirable features for gas sensing as they facilitate rapid gas diffusion and efficient surface reactions [13-15]. Furthermore, thick film sensors fabricated by screen printing are mechanically robust and easily integrated with conventional electronic circuits, making them attractive for practical applications. Operating temperature is another critical parameter that governs the sensing behavior of metal oxide gas sensors. At low temperatures, insufficient thermal energy limits surface reactions, resulting in poor sensitivity. At excessively high temperatures, rapid desorption of gas molecules reduces sensor response. Therefore, achieving high sensitivity at moderate operating temperatures is essential for energy-efficient sensor design. SrO, due to its favorable surface chemistry, is expected to exhibit strong interaction with LPG and other reducing gases at relatively lower operating temperatures compared to conventional metal oxides. Additionally, parameters such as response time, recovery time, selectivity, and concentration-dependent (ppm variation) response are vital for evaluating the practical performance of gas sensors, especially for safety-critical applications like LPG leakage detection [14-16].

The present work focuses on the fabrication of SrO thick films using the screen printing method and a comprehensive investigation of their gas sensing performance toward LPG, CO_2, H_2S, and methanol.

The study emphasizes key sensing parameters including sensitivity, selectivity, gas concentration dependence, and dynamic response–recovery characteristics. Special attention is given to LPG sensing due to its practical relevance and hazardous nature. The results demonstrate that SrO thick films exhibit excellent sensitivity and selectivity toward LPG at a moderate operating temperature, along with fast response and recovery behavior. This study highlights the potential of SrO thick films as promising candidates for low-cost, efficient, and reliable gas sensors suitable for domestic and industrial safety applications.

2. Experimental work

2.1 Preparation of thick films of SrO by screen printing method

The thick films of strontium oxide (SrO) were prepared using a conventional screen printing technique employing commercially available SrO nanoparticles as the sensing material. A paste formulated with a 70:30 weight ratio of inorganic SrO nanoparticles to organic vehicle. The organic vehicle, comprising ethyl cellulose as a temporary binder and butyl carbitol acetate as a solvent, imparted the required thixotropic nature and printability to the paste. The SrO nanoparticles and organic vehicle were thoroughly mixed and ground to obtain a homogeneous paste with uniform dispersion of particles, ensuring good film continuity and adhesion after printing [16, 17]. The prepared paste was screen printed onto thoroughly cleaned glass substrates using a stainless-steel mesh. After deposition, the printed SrO thick films were dried under an infrared (IR) lamp for 25–30 minutes to facilitate slow evaporation of the solvent and partial removal of organic components. This controlled drying process prevented film cracking and ensured uniform film formation. Subsequently, the dried films were annealed at 400 °C for 3 h in a muffle furnace.

2.2 Gas sensing characterization

Figure 1 illustrates the static gas sensing system employed to evaluate the gas sensing performance of the screen-printed SrO thick film sensors. The system mainly consists of a sealed gas chamber, a resistive half-bridge measurement circuit, a temperature-controlled heater assembly, and a controlled gas inlet arrangement. The SrO thick film sensor is mounted on an insulating substrate and placed inside the gas chamber on a heating element. The operating temperature of the sensor is precisely regulated using a temperature controller in combination with a dimmerstat connected to the AC mains, enabling stable and reproducible thermal conditions during sensing measurements. For electrical characterization, the sensor is connected in a half-bridge configuration along with a known reference resistor (R_ref). A constant applied voltage (V_app) is supplied across the circuit, and the voltage drop across the reference resistor (V_ref) is monitored using a digital voltmeter (DVM) [16-18]. Any change in the resistance of the SrO thick film upon exposure to target gases results in a corresponding change in V_ref, which is used to calculate the sensor resistance and sensitivity. This configuration offers high measurement stability and sensitivity to small resistance variations induced by gas–surface interactions. The gas chamber is provided with a gas inlet through which known concentrations of test gases (LPG, CO_2, H_2S, and methanol) are introduced using a calibrated gas injection system. The static mode of operation allows the injected gas to uniformly diffuse and interact with the sensor surface. During exposure, the resistance change of the SrO thick film is continuously recorded as a function of time, enabling the determination of key sensing parameters such as sensitivity, selectivity, response time, and recovery time. After each measurement, the chamber is flushed with air to restore the sensor to its baseline resistance [14, 18-20].

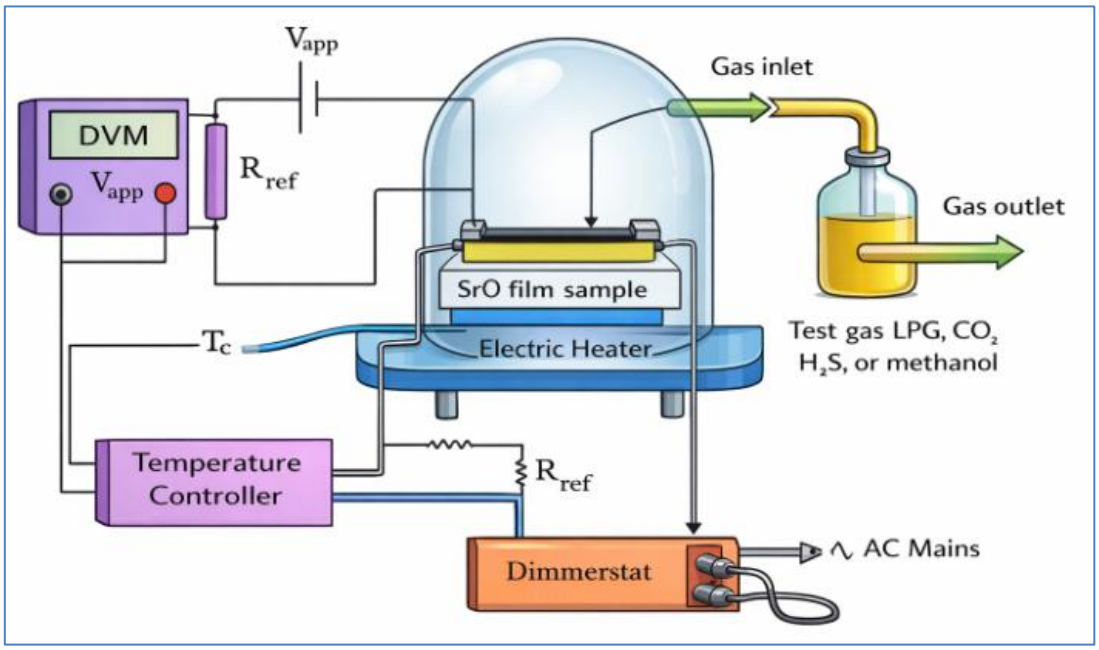

Figure 1: Schematic diagram of static gas sensing system

3. Result and discussion

Figure 2 illustrates the variation of sensitivity of the screen-printed SrO thick films as a function of operating temperature in the range of 50–250 °C toward different test gases, namely LPG, H_2S, CO_2, and methanol. Sensitivity was measured using Eq. 1 [20, 21]

$$\text{Sensitivity (\%)} = \frac{Ra-Rg}{Ra} \times 100 \qquad (1)$$

Where,

Ra - Resistance of a thick film in air and Rg - Resistance of thick film presence of gas.

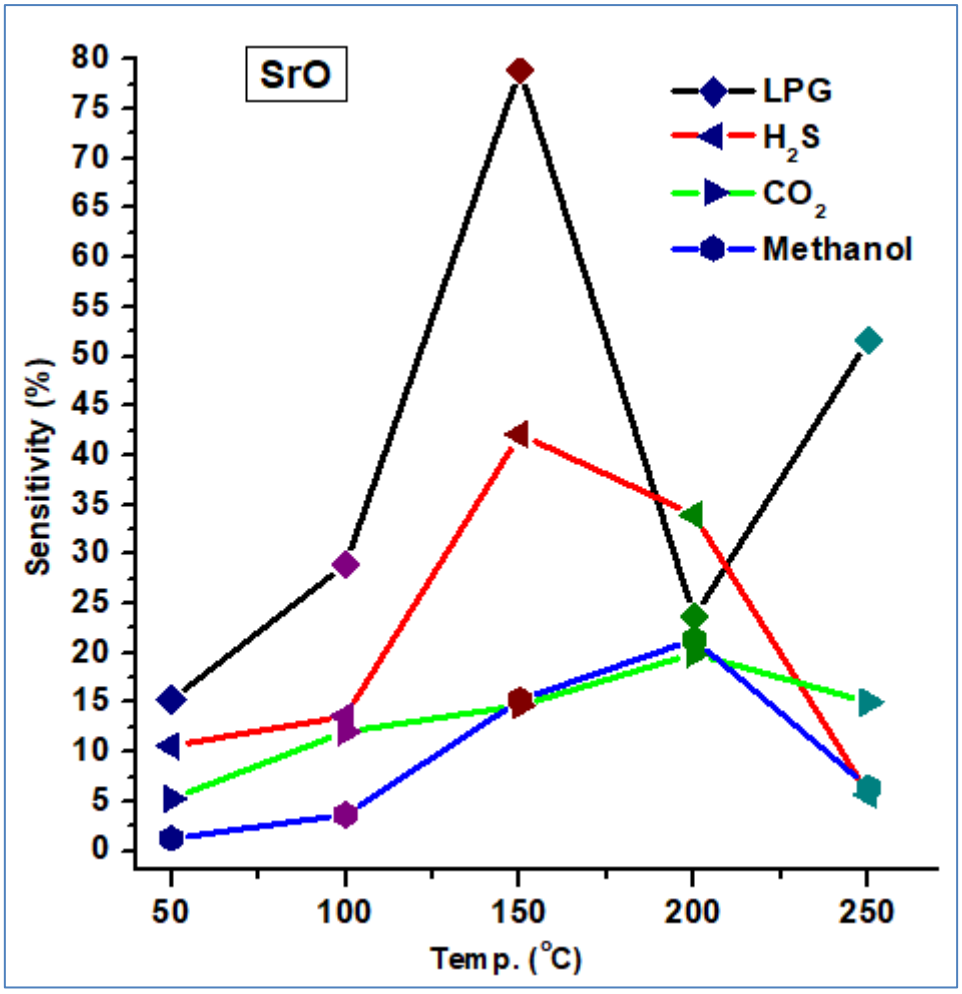

Figure 2: Sensitivity versus operating temperature plot of SrO films

It is evident from the plot and the corresponding data that the gas response of the SrO films is strongly temperature dependent, which is a characteristic feature of chemoresistive metal oxide gas sensors. At lower temperatures (50–100 °C), the sensitivity toward all gases remains relatively low, which can be attributed to insufficient thermal energy for effective adsorption of gas molecules and activation of surface reactions between the target gases and chemisorbed oxygen species on the SrO surface. As the operating temperature increases to 150 °C, a pronounced enhancement in sensitivity is observed, particularly for LPG [21-23]. The SrO films exhibit a maximum sensitivity of 78.96% toward LPG at 150 °C, which is significantly higher than that for H_2S (42.11%), CO_2 (14.68%), and methanol (15.24%) at the same temperature. This behavior indicates strong and preferential interaction of LPG molecules with the basic surface sites of SrO, leading to efficient reaction with adsorbed oxygen ions and a substantial change in film resistance. The sharp peak in LPG sensitivity at 150 °C suggests that this temperature provides optimal kinetics for adsorption–reaction–desorption processes on the SrO surface. Upon further increase in operating temperature to 200 °C, the sensitivity toward LPG decreases markedly to 23.68%, while moderate responses are observed for H_2S (33.95%), CO_2 (19.93%), and methanol (21.36%). This reduction in LPG response at higher temperature is mainly due to rapid desorption of gas molecules from the sensor surface, which limits their effective interaction time. At 250 °C, the sensitivity toward LPG again increases to 51.6%, whereas the responses toward H_2S and methanol decrease significantly, and CO_2 shows only a moderate response [23-25].

Figure 3 depicts the selectivity histogram of the screen-printed SrO thick films toward different test gases, namely LPG, H_2S, CO_2, and methanol, evaluated at the optimum operating temperature. Selectivity is defined as the relative response of the sensor toward a target gas compared to other interfering gases at the same concentration and operating conditions. The histogram clearly demonstrates that the SrO thick films exhibit excellent selectivity toward LPG, with a normalized selectivity value of 100%, indicating a dominant and preferential sensing response to LPG [25, 26]. In comparison, the selectivity toward H_2S is significantly lower, with a value of approximately 53.31%, while much weaker responses are observed for CO_2 (≈18.59%) and methanol (≈19.30%). The pronounced selectivity toward LPG can be attributed to the strong interaction between LPG molecules and the highly basic surface sites of SrO, which promotes enhanced adsorption and efficient surface reactions with chemisorbed oxygen species. This interaction results in a larger release of charge carriers and a substantial change in the electrical resistance of the SrO film. On the other hand, CO_2, being a relatively stable and less reactive gas, and methanol, having different adsorption and reaction kinetics, exhibit comparatively weaker interactions with the SrO surface, leading to lower sensor responses [18-21]. The moderate selectivity observed for H_2S suggests partial interaction with the SrO surface; however, it remains considerably lower than that for LPG, thereby minimizing cross-sensitivity effects.

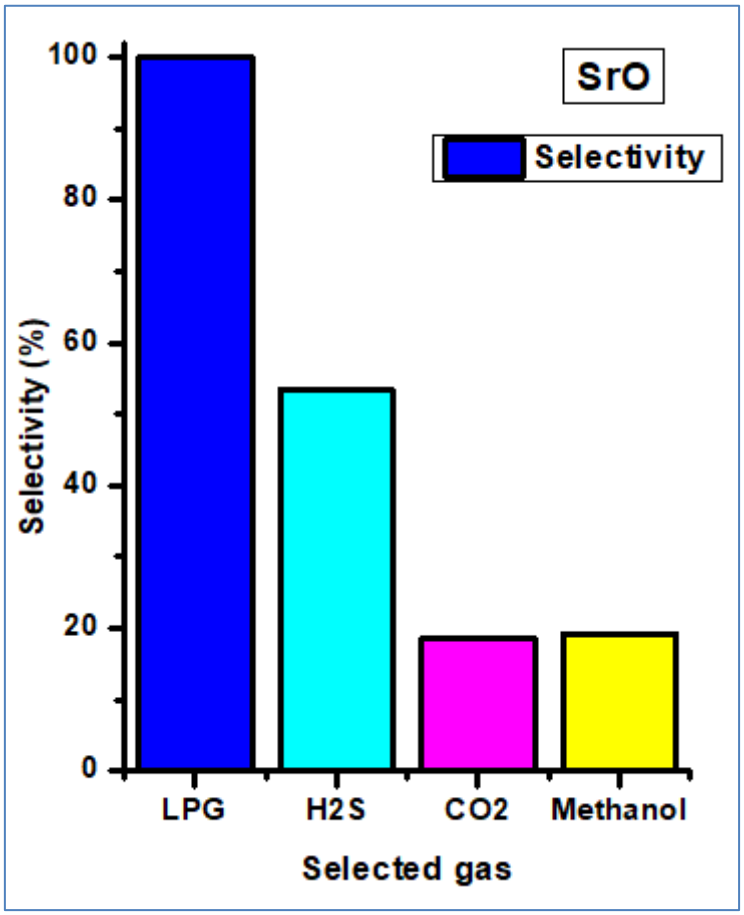

Figure 3: Selectivity histogram of SrO films

Figure 4 illustrates the variation of sensitivity of the screen-printed SrO thick films as a function of LPG concentration in the range of 100–1000 ppm at the optimum operating temperature of 150 °C. The

plot clearly shows that the sensitivity of the SrO films increases significantly with an increase in LPG concentration from 100 to 500 ppm, indicating effective interaction between LPG molecules and the active surface sites of the SrO sensing layer. At a low concentration of 100 ppm, the sensor exhibits a sensitivity of 23.65%, which increases sharply to 45.82% at 200 ppm, reflecting enhanced adsorption of LPG molecules and increased surface reaction kinetics with chemisorbed oxygen species [23, 25]. The maximum sensitivity of 78.96% is observed at an LPG concentration of 500 ppm, suggesting that this concentration provides optimal surface coverage and efficient charge transfer processes on the SrO surface. This pronounced increase in sensitivity with concentration can be attributed to the availability of a large number of active adsorption sites and the strong chemoresistive interaction between the reducing LPG molecules and the oxygen species adsorbed on the SrO surface, leading to a substantial modulation of electrical resistance [25, 26].

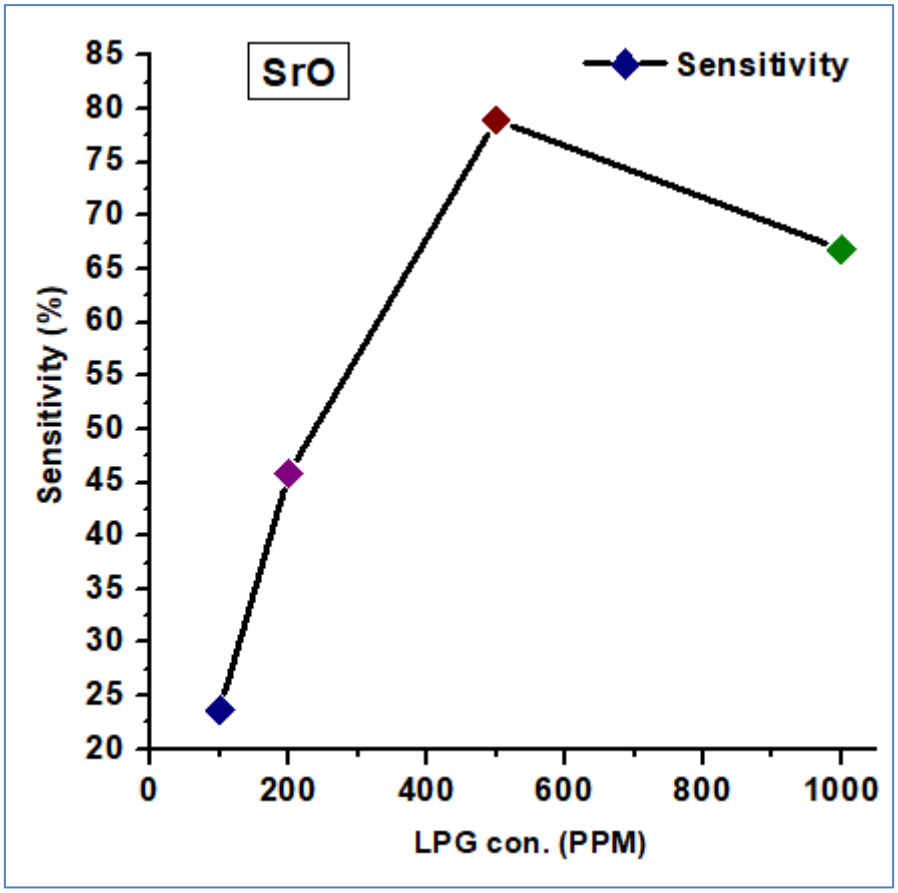

Figure 4: Sensitivity versus LPG concentration plot of SrO films

However, when the LPG concentration is further increased to 1000 ppm, the sensitivity decreases to 66.84%. This reduction at higher concentration is likely due to partial saturation of the available adsorption sites and limitations in further charge carrier modulation, resulting in a sub-linear response.

Figure 5 shows the dynamic response–recovery characteristics of the screen-printed SrO thick films toward LPG at the optimum operating temperature of 150 °C. The plot represents the variation of sensitivity with time during successive cycles of gas exposure (ON state) and gas removal (OFF state). Upon introduction of LPG into the sensing chamber, the sensitivity of the SrO film increases rapidly, indicating a fast response of the sensor due to immediate interaction between LPG molecules and the

chemisorbed oxygen species present on the SrO surface. The sensor reaches nearly 90% of its maximum response within a short duration, and the response time is determined to be approximately 16 s, demonstrating efficient adsorption and rapid surface reaction kinetics. When the LPG supply is switched off and the sensing chamber is flushed with air, the sensitivity decreases sharply, returning close to its baseline value. This decay corresponds to the desorption of LPG molecules and re-adsorption of oxygen species on the SrO surface. The recovery time is found to be about 53 s, indicating effective reversibility of the sensing process and good regeneration capability of the sensing layer [26-28]. The repeatability of the response–recovery cycles observed in the plot confirms the stable and reproducible sensing behavior of the SrO thick films. The fast response and reasonably quick recovery characteristics can be attributed to the porous microstructure of the screen-printed SrO films, which facilitates rapid gas diffusion and efficient exchange of adsorbed species [29, 30].

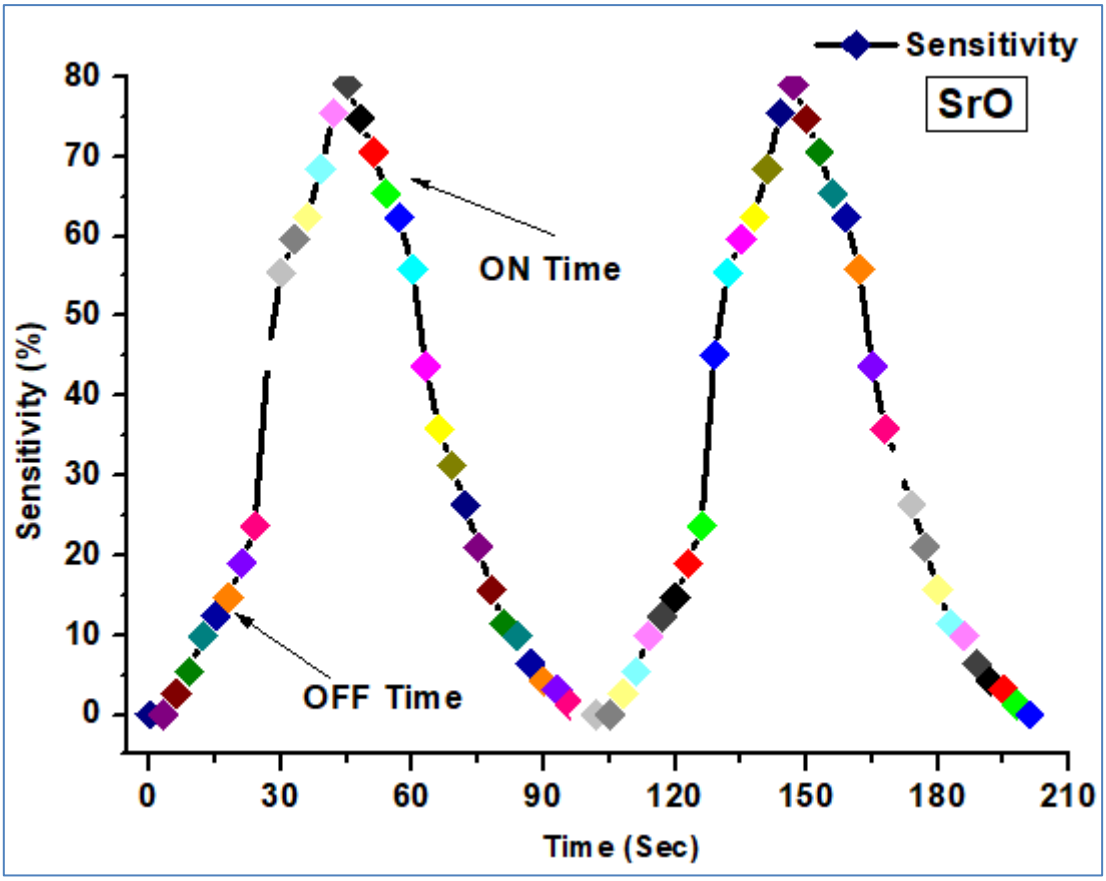

Figure 5: Response and recovery time plot of SrO films

Conclusions

In the present investigation, strontium oxide (SrO) thick films were successfully fabricated using the simple, cost-effective, and scalable screen printing technique with commercially available SrO nanoparticles. The optimized paste composition (70:30 inorganic to organic ratio), controlled drying under an IR lamp, and subsequent annealing at 400 °C for 3 h resulted in mechanically stable, porous, and well-adhered thick films, which are highly suitable for gas sensing applications. The gas sensing performance of the SrO thick films was systematically evaluated toward LPG, H_2S, CO_2, and methanol using a static gas sensing system. The sensing characteristics were found to be strongly dependent on the

operating temperature. Among the tested temperatures, an optimum operating temperature of 150 °C was identified, at which the SrO films exhibited a maximum sensitivity of 78.96% toward LPG at a concentration of 500 ppm. In comparison, significantly lower responses were observed for H_2S, CO_2, and methanol, confirming the preferential sensing behavior of SrO films toward LPG. Selectivity studies further demonstrated excellent discrimination capability of the SrO thick films, with LPG showing a normalized selectivity of 100%, while H_2S, CO_2, and methanol exhibited much lower selectivity values. The sensitivity versus LPG concentration studies revealed a strong concentration-dependent response, with sensitivity increasing from 23.65% at 100 ppm to a maximum at 500 ppm, followed by a slight decrease at higher concentration due to partial saturation of active surface sites. Dynamic response analysis indicated fast sensing kinetics, with a response time of 16 s and a recovery time of 53 s, highlighting efficient adsorption–desorption processes and good reversibility of the sensing mechanism. The results confirm that screen-printed SrO thick films possess high sensitivity, excellent selectivity, moderate operating temperature, and fast response–recovery characteristics toward LPG. These attributes make SrO thick films promising candidates for low-cost, reliable, and efficient LPG gas sensors for domestic and industrial safety applications.

Future scope

The encouraging gas sensing performance of the screen-printed SrO thick films toward LPG opens several avenues for further research and development. Future studies may focus on tailoring the microstructure of SrO films by controlling particle size, film thickness, and porosity to further enhance sensitivity and lower the operating temperature. Incorporation of noble metal catalysts such as Pd, Pt, or Au, or the formation of SrO-based composites and heterostructures with other metal oxides, could be explored to improve selectivity, response–recovery speed, and long-term stability through enhanced surface reaction kinetics. From an application perspective, integration of SrO thick film sensors with low-power microheaters, portable electronics, and wireless monitoring systems could facilitate the development of compact and energy-efficient gas sensing devices.

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