**CO₂ Sensing Performance of Carbon Black-Doped Europium Oxide Thick-Film Sensors**

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In this study, a carbon black-doped europium oxide (Eu₂O₃) thick-film gas sensor was developed and systematically evaluated for CO₂ sensing applications. The sensing layers were fabricated using a screen-printing technique, with Eu₂O₃ paste prepared with an organic binder, followed by the incorporation of carbon black at different doping concentrations (0.1-5 wt.%). The structural and compositional characteristics of the films were investigated using field-emission scanning electron microscopy (FESEM) and energy-dispersive X-ray spectroscopy (EDX), while their electrical properties were evaluated through current-voltage (I-V) measurements. Gas-sensing performance was investigated in a controlled chamber with CO₂ concentrations ranging from 1000 to 5000 ppm. The results revealed that the carbon black incorporation significantly improved the microstructure of the sensing film by reducing particle agglomeration and generating a more porous, uniform morphology, thereby facilitating gas diffusion and charge transport. Among the tested samples, the sensor with 2 wt.% carbon black doping exhibited the best performance, achieving high linearity (97.66%) and enhanced sensitivity of 0.05327 mV/ppm compared with the undoped Eu₂O₃ sensor (0.01476 mV/ppm). The optimized sensor exhibited good repeatability, satisfactory stability, and reduced hysteresis during successive CO₂ exposure cycles. These improvements may be attributed to the formation of conductive pathways and the increased availability of active surface sites introduced by carbon black within the Eu₂O₃ matrix. The results establish carbon black-modified Eu₂O₃ thick films as promising candidates for room-temperature CO₂ gas sensing, with competitive sensing performance.

Keywords: Carbon dioxide sensor, Europium oxide, Carbon black doping, Thick-film gas sensor, Screen-printing technique.

INTRODUCTION

Carbon dioxide (CO₂) is a major greenhouse gas that plays an essential role in the Earth's natural carbon cycle. It is released through natural processes such as respiration, volcanic activity and the decomposition of organic matter. Human activities, particularly fossil fuel combustion and deforestation, have substantially increased its atmospheric concentration. Methane (CH₄) and nitrous oxide (N₂O) are other major greenhouse gases that contribute to global warming by trapping heat in the atmosphere [1]. Rising greenhouse gas emissions have intensified climate change concerns and encouraged research into CO₂ capture, reduction and utilization technologies [2,3]. Carbon capture, utilization and storage (CCUS) has emerged as an important approach to reducing CO₂ emis-

sions, although leakage from storage sites may adversely affect groundwater, soil and surrounding ecosystems [4]. Reliable gas sensors are consequently required for environmental monitoring, industrial safety, air quality assessment and the early detection of potential CO₂ leakage.

Several gas-sensing technologies have been developed, such as metal-oxide semiconductor (MOS), electrochemical, non-dispersive infrared (NDIR), catalytic combustion and photoionization detector (PID) sensors. Among these, MOS sensors have attracted considerable research interest owing to their compact design, relatively low fabrication cost, chemical stability and compatibility with different sensing applications [5,6]. Materials such as SnO₂, ZnO and WO₃ are widely investigated for gas detection due to their sensitivity, stability and interaction with gas molecules [7,8]. Their sensing per-

formance can be improved through nanostructuring, doping and surface functionalization, which modify the electronic properties of the sensing layer and increase the availability of active sites for gas adsorption. Nanostructured architectures can provide a larger surface area for gas-solid interactions, potentially enhancing sensitivity and detection efficiency [9]. The relatively low cost of MOS materials further supports their application in environmental monitoring and Internet of Things (IoT)-based sensing systems [10].

Europium oxide (Eu_2O_3) has emerged as a potential sensing material for CO_2 detection. Previous experimental findings have established that Eu_2O_3 thick films can detect CO_2 at room temperature. The interaction of CO_2 molecules with Eu^{3+} ions on the Eu_2O_3 surface was reported to initiate a redox process, increasing the charge-carrier concentration and electrical conductivity of the sensing material. These electrical changes enable the detection of different CO_2 concentrations [11]. Despite these promising characteristics, the sensing response of Eu_2O_3 may be further improved through suitable material modification strategies.

Carbon black is a potential additive for modifying the electrical and gas-sensing properties of semiconductor materials. Its incorporation can alter the conductive network within a sensing layer, affecting its electrical resistance and response to target gases [12,13]. Previous studies have reported improved sensitivity in carbon-black-doped zinc oxide sensors [14]. Carbon incorporation derived from carbon black has also been associated with changes in the electronic structure and carrier concentration of semiconductor sensing materials, which can influence their gas-detection performance [15]. These findings provide a basis for investigating carbon black as a modifier of Eu_2O_3 -based sensing materials, particularly with respect to its influence on conductivity and CO_2 adsorption.

Screen printing is widely used for thick-film sensor fabrication owing to its simplicity, cost-effectiveness and suitability for depositing sensing materials onto different substrates. The technique allows controlled deposition and adjustment of film thickness, supporting the preparation of uniform sensing layers [16]. It is suitable for fabricating compact sensing elements with useful mechanical and electrical characteristics. Screen printing further allows flexibility in electrode dimensions and design, making it applicable to customized sensor configurations [17].

Despite advances in MOS-based gas sensors, the development of low-cost and sensitive CO_2 sensors using carbon black-modified Eu_2O_3 remains less explored. To the best of our knowledge, the influence of carbon black concentration on the CO_2 -sensing characteristics of screen-printed Eu_2O_3 thick films has not been systematically established. In particular, the relationship between carbon black incorporation, film morphology, electrical conductivity and sensing response requires further investigation. Addressing these aspects may help clarify the role of carbon black in modifying Eu_2O_3 -based sensing layers and support the development of practical room temperature CO_2 sensors for environmental monitoring and industrial safety applications.

EXPERIMENTAL

Fabrication of gas sensor thick films sensor: The fabrication process involved three main stages: (i) preparation of the organic binder, (ii) preparation of pure Eu_2O_3 paste and (iii) preparation of carbon black-doped Eu_2O_3 paste. The organic binder was prepared by mixing approximately 0.5 g of ethyl cellulose with 9.5 g of terpineol [11,18]. The weighed components were transferred into a beaker containing a magnetic stir bar and stirred at 200 rpm for 24 h at 40 °C using a hotplate stirrer to obtain a homogeneous mixture. Gloves were worn throughout the procedure to minimize direct chemical contact.

Pure Eu_2O_3 paste was prepared by gradually adding 1 g of Eu_2O_3 powder to approximately 1.4430 g of the organic binder. The binder quantity was adjusted to compensate for material loss during transfer and adhesion to the glass surface. The mixture was stirred at 80 rpm and 30 °C until a homogeneous paste was obtained. For carbon black-doped Eu_2O_3 , the required quantities of Eu_2O_3 and carbon black were weighed according to the doping concentrations listed in Table-1. The powders were transferred into a beaker and approximately 40 mL of acetone was added as a dispersing solvent. The beaker was sealed with parafilm to minimize solvent evaporation and contamination. The suspension was ultrasonicated for 30 min at 50 °C to improve particle dispersion. It was then dried in a vacuum oven for 4 h to remove acetone. The dried powder was ground using a porcelain mortar and pestle to obtain a fine, uniform mixture and stored in a vial for subsequent use.

TABLE-1
WEIGHT PERCENTAGE OF Eu_2O_3 DOPED CARBON BLACK

Europium oxide (Eu_2O_3)		Carbon black (CB)	
Amount (g)	%	Amount (g)	%
0.999	99.9	0.001	0.1
0.995	99.5	0.005	0.5
0.990	99.0	0.010	1.0
0.980	98.0	0.020	2.0
0.950	95.0	0.050	5.0

For the 0.2 wt.% carbon black-doped paste, 0.998 g of Eu_2O_3 and 0.002 g of carbon black were mixed with approximately 1.4430 g of the organic binder. The powders were added gradually and stirred at 80 rpm and 30 °C until a homogeneous paste was formed. The thick-film sensors were fabricated on Kapton polyimide flexible substrates with a thickness of approximately 100 μm . Kapton was selected for its flexibility, thermal stability and electrical insulation properties. Silver conductive paste was first screen-printed onto the substrate to form the interdigitated electrode (IDE) structure. The printed electrodes were fired at 150 °C for 15 min to improve adhesion and electrical conductivity. The Eu_2O_3 -based sensing paste was then deposited onto the IDE structure using screen printing. The fabricated sensors were annealed at 200 °C for 1 h under ambient conditions in a vacuum oven to improve the structural stability of the sensing layer. The fabrication of the Eu_2O_3 layer on the substrate. The average thickness of the deposited sensing layer was approximately 0.2 mm after screen printing and annealing. Multiple sensors were fabricated at each doping

concentration under identical processing conditions to ensure reproducibility. The paste composition, screen-printing parameters, drying conditions and annealing temperature were kept consistent across the samples.

Electrical Characterization: The fabricated thick-film sensor was placed inside a controlled chamber and connected to a picoammeter to measure its current-voltage (I-V) characteristics. The measurements were used to evaluate the electrical behaviour of the sensor and determine whether it exhibited ohmic conduction, characterized by a linear relationship between current and applied voltage. Sensor resistance (R) was calculated from the I-V curve and electrical conductance was determined as its reciprocal (1/R). These parameters were used to examine charge transport and assess the influence of carbon black incorporation on the electrical properties of the sensing films.

Structural and morphological characterization: The structural, morphological and compositional characteristics of the Eu₂O₃/carbon black (Eu₂O₃/CB) thick films were investigated using field-emission scanning electron microscopy (FESEM) and energy-dispersive X-ray spectroscopy (EDX). The micrographs were analyzed to assess changes in particle dispersion, surface roughness and structural uniformity following carbon black incorporation. Particular attention was given to porous structures and interconnected particles, which may facilitate gas diffusion, adsorption and charge transport. EDX analysis was performed to determine the elemental composition and distribution within the films. The presence of europium (Eu), oxygen (O) and carbon (C) was examined to assess the incorporation of carbon black into the Eu₂O₃ matrix.

Gas-sensing measurements: The gas-sensing performance of six thick-film sensors with different carbon black doping concentrations was evaluated using a controlled gas-delivery system. Before each measurement cycle, a vacuum pump was operated to remove residual gases and contaminants from the chamber. Nitrogen gas was introduced as a purge and carrier gas to establish a stable baseline. Certified CO₂ gas was then introduced gradually and the concentration was increased stepwise from 1000 to 5000 ppm, using increments of 1000 ppm. The sensor response was evaluated by continuously recording changes in the output voltage.

Measurements were conducted under room temperature laboratory conditions at approximately 26 °C and 50% relative humidity (RH). An SCD41 CO₂ sensor integrated with an ESP32 data acquisition system was used to monitor the CO₂ concentration inside the chamber. Temperature and humidity readings were recorded during the experiments, although humidity was not actively controlled. The target CO₂ concentrations were verified using the SCD41 readings.

The electrical output of the Eu₂O₃-based sensing film was measured using a 10 MΩ voltage-divider circuit connected to an ADS1115 analog-to-digital converter. The resistor value was selected to obtain measurable voltage variations from the sensor, whose resistance was in the megaohm-to-gigaohm range, while limiting loading effects. The digitized signal was processed by the ESP32 microcontroller for real-time monitoring and data logging. The experiments were conducted under static chamber conditions without active control of the gas flow rate.

A custom-designed Node-RED monitoring system was used for real-time visualization and automatic data acquisition. The recorded data were subsequently analyzed to compare the electrical and gas-sensing characteristics of the fabricated films.

Optimization of doping concentration: The optimal carbon black doping concentration was identified through a comparative assessment of the electrical, morphological, compositional and gas-sensing results. The evaluation considered sensitivity toward CO₂, response-recovery behaviour, stability, repeatability and electrical conductivity. The selected concentration was determined by balancing these parameters to identify a composition suitable for room temperature CO₂ detection.

Analysis of performance parameters for undoped Eu₂O₃ and optimized Eu₂O₃/CB gas sensors at various CO₂ concentrations: The gas-sensing performance of undoped Eu₂O₃ and optimized Eu₂O₃/CB thick-film sensors was evaluated at different CO₂ concentrations. The investigation focused on the influence of carbon black incorporation on sensitivity, signal stability, repeatability and hysteresis. Measurements were performed under identical experimental conditions to ensure a consistent comparison between the sensors.

Sensor stability was assessed by exposing the sensing film to a fixed CO₂ concentration and continuously monitoring its output voltage for 600 s under steady-state conditions. The recorded voltage was plotted against time to examine signal drift and response consistency during exposure. Repeatability was investigated through successive CO₂ exposure-purge cycles at a fixed concentration under identical operating conditions. The output voltage recorded during each cycle was compared and the response was plotted against time or cycle number to evaluate the reproducibility of the sensing signal.

Hysteresis was examined by increasing the CO₂ concentration stepwise to 5000 ppm and subsequently decreasing it to the initial concentration. The steady-state voltage was recorded at each concentration during both the increasing and decreasing sequences. The corresponding response-concentration curves were compared to assess hysteresis and potential memory effects in the sensing material. The results from these measurements were used to compare the sensing characteristics of undoped Eu₂O₃ and optimized Eu₂O₃/CB thick films. Sensitivity, response behaviour, stability, repeatability and hysteresis were considered when assessing the effect of CB incorporation and identifying the optimized doping concentration. These evaluations provided insight into the operational consistency and reliability of the sensors during repeated CO₂ exposure.

RESULTS AND DISCUSSION

The fabricated Eu₂O₃ thick-film sensors were examined to compare the surface appearance and coloration of undoped and carbon black-doped samples. The films became progressively darker as the carbon black concentration increased, as shown in Fig. 1. The electrical resistance of the sensors was measured at carbon black concentrations of 0% (undoped Eu₂O₃), 0.1%, 0.5%, 1%, 2% and 5%. Their gas-sensing responses were evaluated over a CO₂ concentration range of 1000-

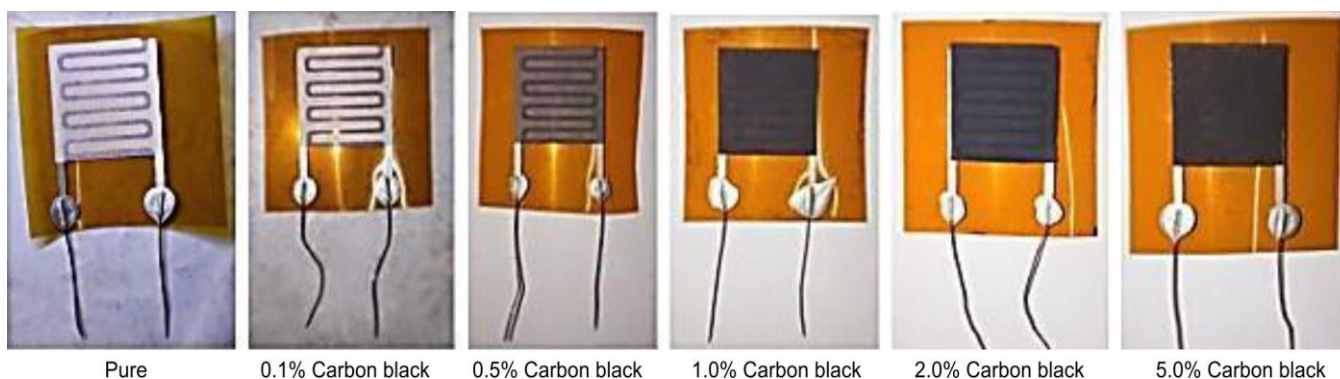


Fig. 1. Visual comparison of pure and carbon black-doped Eu_2O_3 thick films

5000 ppm. Differences in output voltage were analyzed to examine the effect of carbon black content on charge transport and gas-sensing behaviour. These measurements were used to examine the relationship between carbon black concentration, electrical resistance and CO_2 -sensing response and to identify a suitable doping concentration for the fabricated thick film sensors.

Morphological studies: The surface morphology and microstructural characteristics of the Eu_2O_3 thick films were investigated using FESEM at a magnification of $\times 100,000$. The undoped Eu_2O_3 film and the film containing 2 wt.% carbon black exhibit distinct morphological features.

The undoped Eu_2O_3 film (Fig. 2a) displays a highly agglomerated, cauliflower-like morphology composed of densely packed and irregular spherical nanoparticle clusters. Such aggregation is commonly associated with the high surface energy of nanoparticles, which promotes interparticle attraction and clustering [19]. The resulting surface is rough and non-uniform, with poorly defined grain boundaries and limited structural organization.

In comparison, 2 wt.% CB-doped Eu_2O_3 film (Fig. 2b) exhibits a more uniform and dispersed morphology. Some particles appear partially separated, while elongated and interconnected features are visible in several regions. These changes suggest that CB incorporation may influence particle arrange-

ment during film formation, reducing excessive clustering and improving microstructural uniformity [20].

The FESEM observations reveal morphological differences between the undoped and carbon black-doped films that may affect their electrical and gas-sensing properties. The more dispersed structure and apparent interparticle connections in the doped film may support charge transport, while accessible pores and surface regions may facilitate CO_2 diffusion and gas-surface interactions. These features could contribute to the sensing response of the carbon black-doped film, although their specific roles require correlation with electrical measurements and gas-sensing results [21,22]. The observed morphology is consistent with the possibility of improved electrical transport and CO_2 -sensing performance compared with the undoped Eu_2O_3 film.

The elemental composition and atomic distribution of the carbon black-doped Eu_2O_3 composite thick films were investigated using energy-dispersive X-ray (EDX) spectroscopy. Fig. 3 confirms the presence of carbon (C), oxygen (O) and europium (Eu) in the composite film. The measured weight and atomic percentages verify the successful incorporation of carbon black into the Eu_2O_3 matrix without introducing unintended impurities.

The corresponding SEM micrograph (Fig. 4a) reveals an agglomerated and porous microstructure of carbon black-

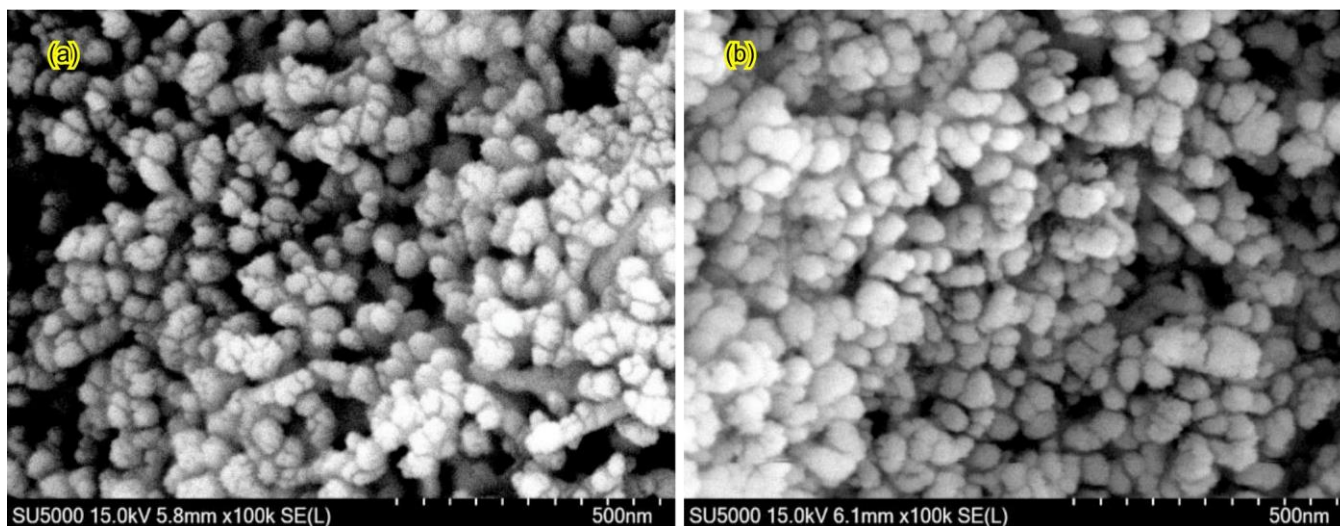
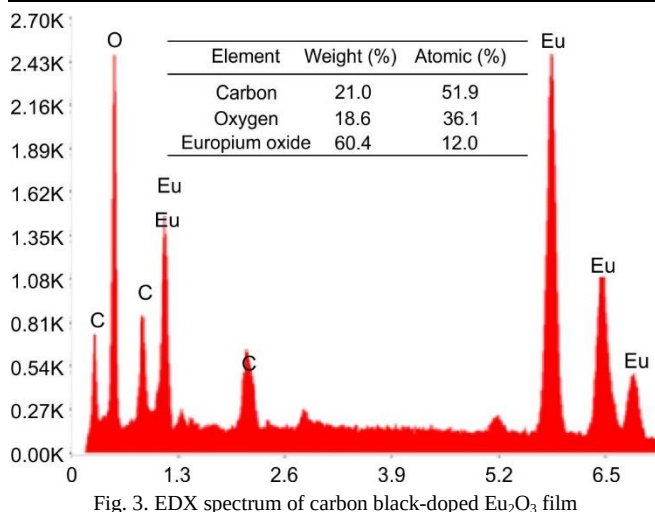


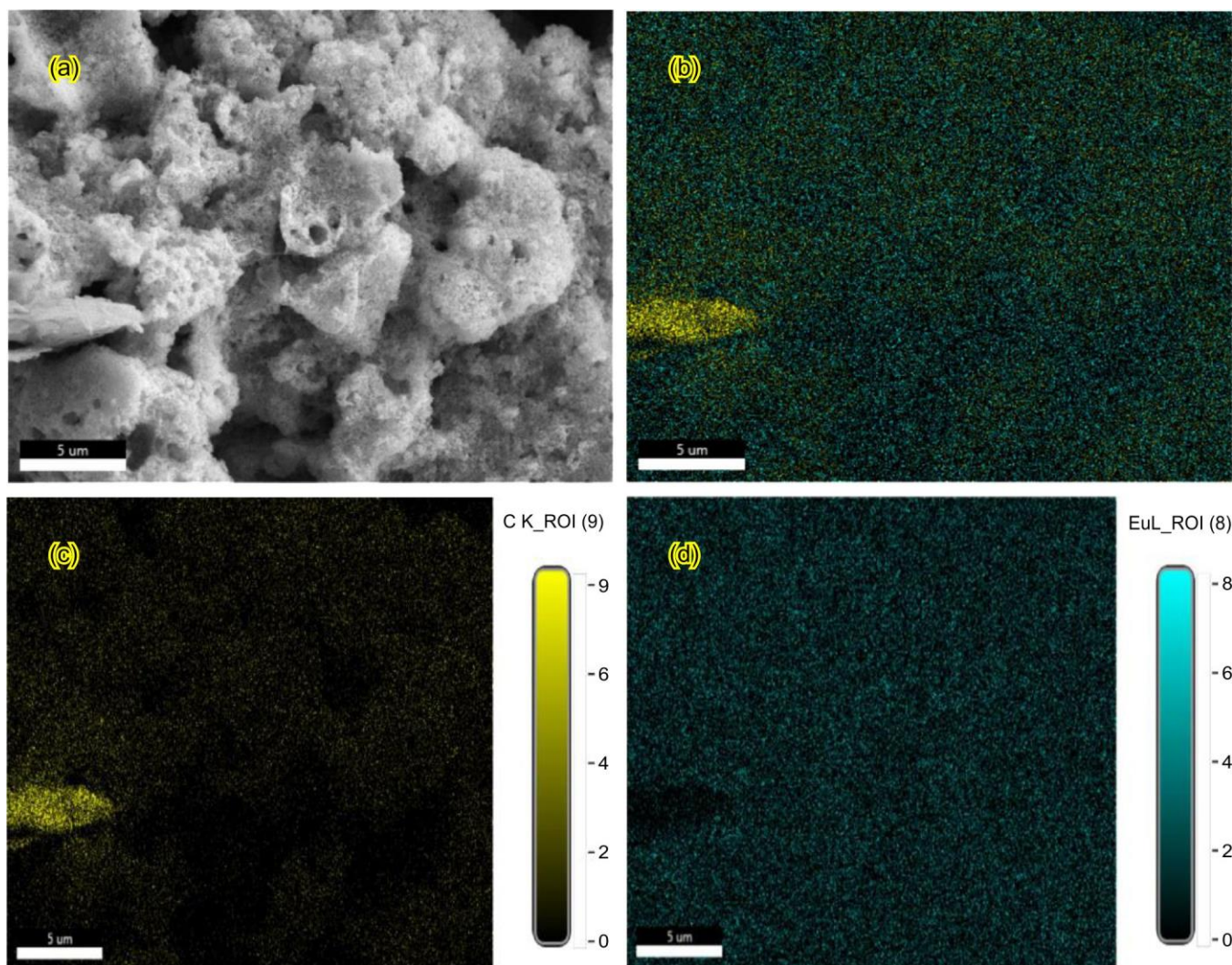
Fig. 2. FESEM images of pure Eu_2O_3 (a) and CB-doped Eu_2O_3 (b) films

Fig. 3. EDX spectrum of carbon black-doped Eu₂O₃ film

doped Eu₂O₃ nanoparticle assemblies. The surface morphology appears continuous and structurally intact, with no evidence of distinct secondary phases or large foreign particulates. This observation indicates that the composite film retains the structural integrity after doping.

The EDX elemental mapping (Fig. 4b) provides spatial distribution information for the detected elements. The carbon map (Fig. 4c) shows a relatively uniform distribution of carbon throughout the scanned region. The absence of localized carbon rich clusters or segregated domains suggests that the carbon black is uniformly distributed within the Eu₂O₃ matrix, which confirmed the effective mixing and strong interfacial interaction between the conductive carbon phase and the Eu₂O₃ particles. Similarly, the europium mapping (Fig. 4d) confirms a uniform distribution of Eu across the entire microstructure, demonstrating that the primary Eu₂O₃ phase remains continuous and structurally preserved after carbon incorporation. Thus, the oxide framework showed no apparent elemental depletion or Eu-rich segregation.

The overlapping elemental distribution in the composite mapping further supports the formation of a well-integrated Eu₂O₃/CB composite rather than a simple physical mixture with phase separation. Such homogeneous dispersion is essential for enabling continuous charge-transport pathways within the sensing layer. The formation of an interconnected conductive network is particularly beneficial for gas sensing and electrochemical applications, as it enhances electrical cond-

Fig. 4. SEM image and elemental mapping overlays of (a) carbon black-doped Eu₂O₃, (b) dopant element, (c) carbon black and (d) Eu₂O₃

activity, improves electron mobility and increases surface reactivity, ultimately contributing to improved sensor performance [19].

Analysis of performance parameters for undoped Eu_2O_3 and optimized $\text{Eu}_2\text{O}_3/\text{CB}$

Pure Eu_2O_3 sensor: The resistance of the pure Eu_2O_3 sensor was calculated from the slope of the linear region of its I-V curve. A lower resistance corresponds to higher electrical conductivity and may be associated with more effective charge transport and good electrode-film contact. Fig. 5 shows the I-V characteristics of the pure Eu_2O_3 sensor measured over a voltage range of -1 to +1 V. The curve exhibits a linear and nearly symmetric response under positive and negative bias, consistent with ohmic conduction at the electrode-film interface. No pronounced non-linearity or hysteresis is apparent within the measured voltage range.

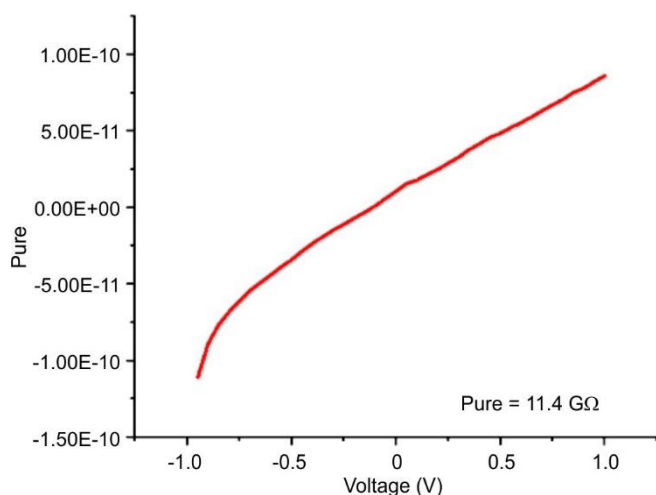


Fig. 5. I-V characteristic curve of pure Eu_2O_3

The resistance calculated from the linear-region slope was approximately 11.4 GΩ. This high resistance is consistent with the electrical properties of the Eu_2O_3 sensing layer and may be affected by fabrication parameters such as the screen-printed

film thickness and post-deposition annealing temperature and duration. These parameters can influence the film microstructure, grain connectivity and available charge-transport pathways. The linear I-V response supports the electrical integrity of the fabricated pure Eu_2O_3 sensor and is consistent with ohmic contact between the electrodes and sensing layer. The formation of a conductive network in the carbon black-doped film should be assessed separately using its I-V measurements and corresponding resistance values.

Eu_2O_3 -doped carbon black: From Fig. 6b, it is observed that the sensor with 5 wt.% carbon black doping exhibits the lowest resistance compared to the 2 wt.%, 1 wt.%, 0.5 wt.% and 0.1 wt.% carbon black-doped samples (Fig. 6a). This trend indicates that increasing the carbon black concentration enhances the electrical conductivity of the Eu_2O_3 -based thin film, with 5 wt.% providing the most significant reduction in resistance among the investigated compositions.

Fabrication-related factors may also contribute to the observed variations in resistance. Parameters such as screen-printed film thickness, paste homogeneity, drying conditions, and annealing temperature and duration can affect the microstructure, grain connectivity and charge-transport behaviour of the sensing layer. Film thickness, in particular, can alter the conduction path length and influence the measured resistance.

The incorporation of carbon black into the Eu_2O_3 matrix enhances electrical conductivity by promoting the formation of interconnected conductive pathways within the oxide framework. At a 5 wt.% doping concentration, the conductive carbon network appears to reach a more effective percolation threshold under the current fabrication conditions, resulting in the lowest resistance. Therefore, based on the I-V analysis, 5 wt.% carbon black doping is considered the optimal composition for electrical performance in the fabricated sensor.

Selection of the optimal carbon black doping concentration for comparative analysis:

Pure and carbon black doped Eu_2O_3 sensors were evaluated to identify a suitable composition for comparative performance analysis. The selection was based primarily on linearity and sensitivity, with the results summarized in Table-2. Among the tested compositions, the sensor containing 2 wt.% carbon black exhibited

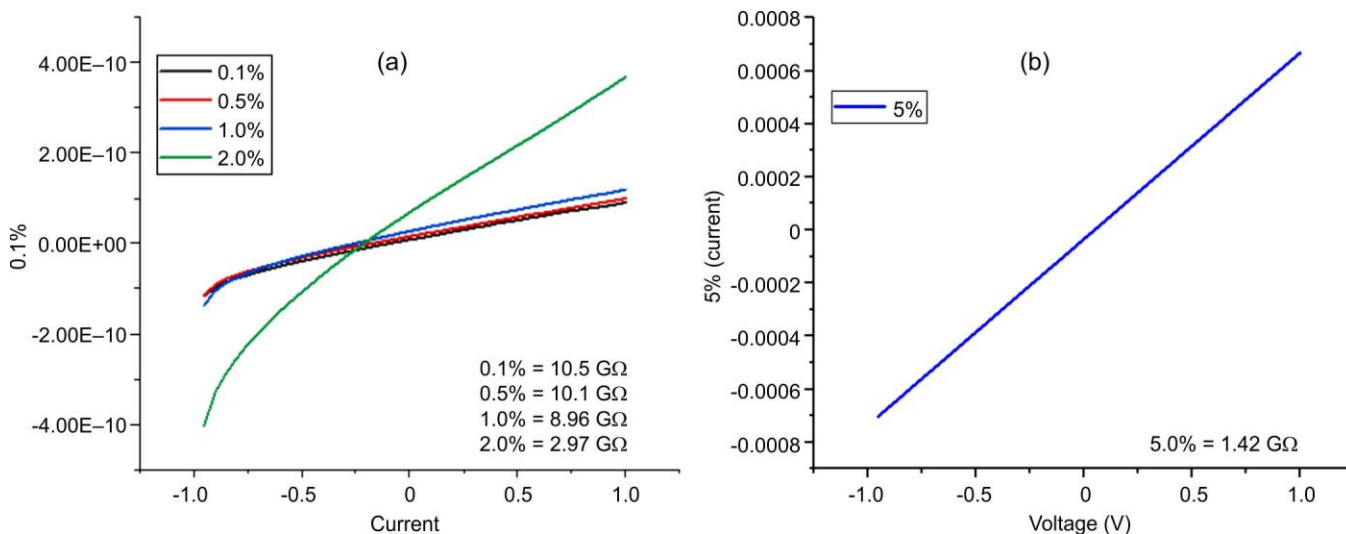


Fig. 6. I-V characteristic curves of Eu_2O_3 -doped carbon black at 0.1%, 0.2%, 0.5%, 1%, 2% (a) and 5% (b)

TABLE-2
COMPARISON OF PERFORMANCE PARAMETERS
BETWEEN PURE AND CARBON BLACK DOPED SENSORS

Parameter	Linearity (%)	Sensitivity ($\mu\text{V/ppm}$)
Pure	96.93	14.76
0.1% CB	38.22	8.25
0.5% CB	89.07	18.5
1.0% CB	67.68	31.55
2.0% CB	97.66	53.27
5.0% CB	89.13	-2.78

the most favourable combination of these parameters. It achieved the highest linearity (97.66%) and the highest positive sensitivity ($53.27 \mu\text{V/ppm}$), providing a highly linear response and a strong output signal with increasing CO₂ concentration. These results supported its selection for comparison with the undoped Eu₂O₃ sensor.

The 5 wt.% carbon black-doped Eu₂O₃ sensor exhibited a relatively high linearity of 89.13%, but its sensitivity was negative ($-2.78 \mu\text{V/ppm}$), corresponding to a change in the observed sensing response from n-type (NPN) to p-type (PNP) behaviour. This change may be associated with the influence of the carbon network at higher carbon black loading. Its different response characteristics could complicate a direct comparison with the undoped sensor, whose sensing behaviour differs from that of the 5 wt.% sample.

The sensors containing lower carbon black concentrations (0.1-1 wt.%) exhibited either lower linearity or lower sensitivity than the 2 wt.% sample. The 0.1 wt.% sensor, for example, had a linearity of only 38.22%. Although the 0.5 and 1 wt.% samples showed improved sensitivity, neither achieved the combination of linearity and sensitivity recorded for

the 2 wt.% carbon black-doped sensor. Based on the measured linearity and sensitivity, the 2 wt.% carbon black-doped Eu₂O₃ sensor was selected as the optimal composition for comparative analysis with the pure Eu₂O₃ sensor under the fabrication and testing conditions used in this study.

Stability studies: The stability of the fabricated sensors was assessed over 600 s at five CO₂ concentrations viz. 1000, 2000, 3000, 4000 and 5000 ppm. The voltage output was monitored over time to examine signal fluctuations and the consistency of the sensor response under steady-state exposure conditions. As shown in Fig. 7, pure Eu₂O₃ sensor exhibits relatively stable voltage responses throughout the measurement period. The output remains nearly constant at each concentration, with only minor fluctuations. The formation of consistent voltage plateaus indicates stable signal behaviour under the tested conditions.

The 2 wt.% carbon black-doped Eu₂O₃ sensor exhibits somewhat higher voltage fluctuations than the pure sensor, although its output remains distinguishable at each CO₂ concentration. These fluctuations may be associated with changes in interparticle connectivity and charge-transport pathways following carbon black incorporation. Despite the variations, the sensor maintains measurable responses across the tested concentration range.

Both sensors exhibit an increasing voltage response as the CO₂ concentration rises from 1000 to 5000 ppm. This trend is consistent with a concentration-dependent sensing response. The stability measurements show that the pure sensor has lower signal fluctuation, while the 2 wt.% carbon black-doped sensor retains distinguishable responses across the concentration range. The stability and sensitivity results can be considered together when comparing the performance of the two sensors.

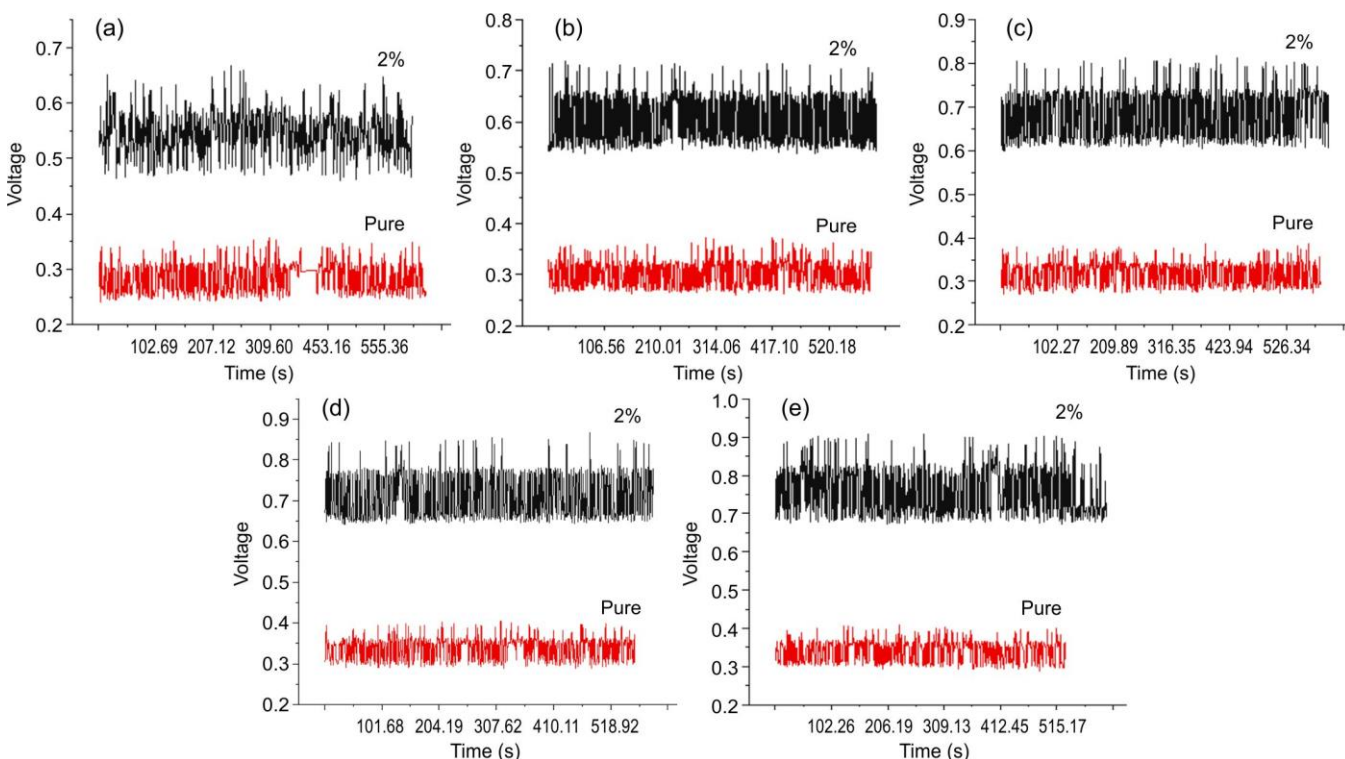


Fig. 7. Comparative stability of the samples under varying CO₂ concentrations: (a) 1000 ppm, (b) 2000 ppm, (c) 3000 ppm, (d) 4000 ppm and (e) 5000 ppm

Sensitivity and repeatability studies: As shown in Table-3, the incorporation of 2 wt.% carbon black into the Eu_2O_3 sensing layer improves its measured electrical and gas-sensing performance compared with the pure sensor. Linearity increases slightly from 96.93% for pure Eu_2O_3 to 97.66% for the carbon black-doped sensor, which indicate a more linear relationship between CO_2 concentration and output response over the investigated range.

Parameter	Pure	Doped (CB)
Linearity (%)	96.93	97.66
Sensitivity (mV/ppm)	0.01476	0.05327
Standard deviation (V)	0.0026	0.00645
Resolution	0.1761	0.1211

The most pronounced improvement is observed in sensitivity, which increases from 0.01476 mV/ppm for the pure sensor to 0.05327 mV/ppm for the 2 wt.% CB-doped sensor, corresponding to an approximately 3.6-fold increase. This enhancement may be associated with more effective charge transport through conductive pathways formed by carbon black within the Eu_2O_3 matrix [23]. The sensing response may involve charge-transfer processes at the material surface. Since nitrogen was used to purge the chamber before CO_2 exposure, the response was measured relative to the purge-gas baseline. CO_2 adsorption at active surface sites may alter the surface charge distribution and carrier concentration, leading to the measurable changes in output voltage. As FESEM analysis revealed a more uniform and dispersed morphology in the carbon black-doped film, which improve gas access to the sensing surface. These structural and electrical changes could contribute to the increased sensitivity. The comparative sensitivity values are shown in Fig. 8.

The standard deviation increases from 0.0026 V for the pure sensor to 0.00645 V for the carbon black-doped sensor. This indicates better absolute variation in the output voltage

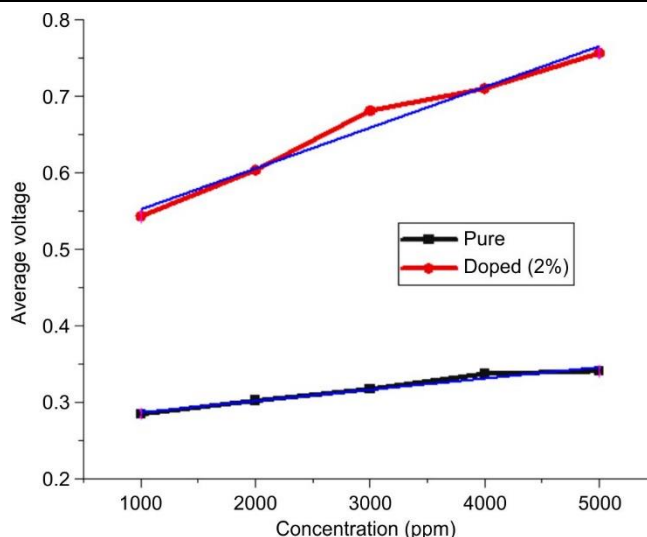


Fig. 8. Average voltage response of pure and 2% carbon black-doped materials at different CO_2 concentrations.

of the doped sensor. Since its response magnitude is higher, the standard deviation should be interpreted alongside the signal amplitude and relative variation. The standard deviation alone is insufficient to establish whether the sensor has lower stability. The reported resolution decreases from 0.1761 for the pure sensor to 0.1211 for the carbon black-doped sensor. If a lower value corresponds to better resolution under the calculation method used, this change indicates an improved ability to distinguish smaller variations in CO_2 concentration. Along with the higher sensitivity and slightly improved linearity, this result supports the enhanced detection capability of the 2 wt.% carbon black-doped sensor.

The repeatability results (Fig. 9) compare the pure and carbon black-doped Eu_2O_3 sensors over repeated CO_2 exposure cycles. The carbon black-doped sensor exhibits higher output voltages across the measurement runs, which is consistent with its higher sensitivity. The repeated measurements remain closely aligned and support the good repeatability under the tested conditions.

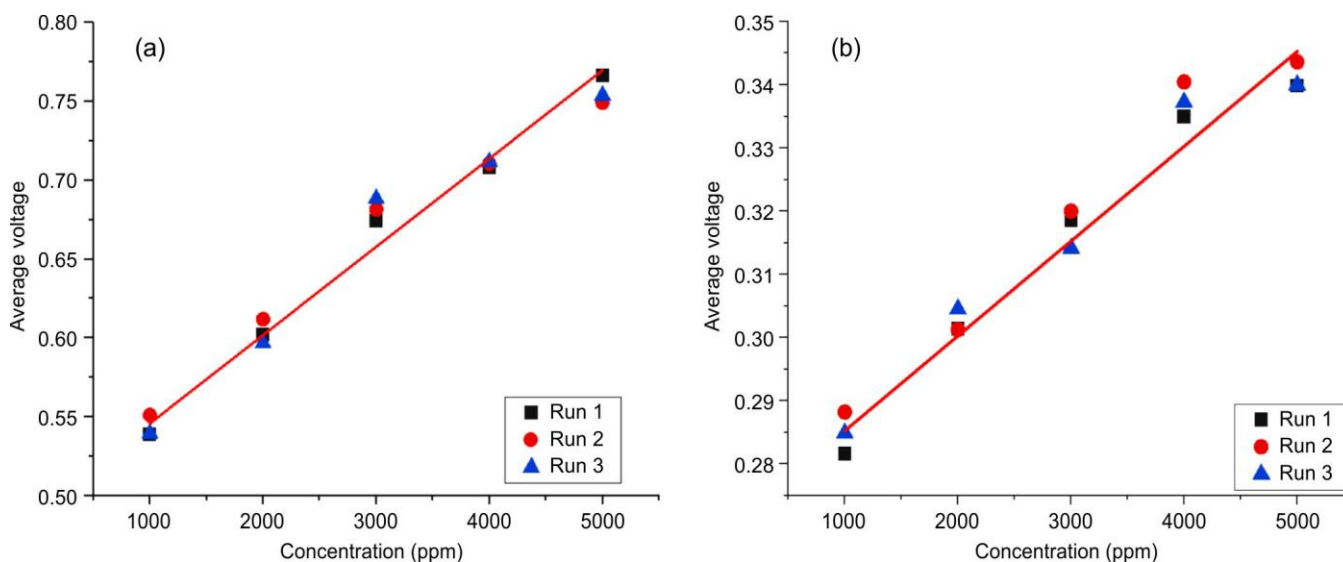


Fig. 9. Repeatability performance of (a) 2 wt.% carbon black-doped and (b) pure Eu_2O_3 sensors

For the pure sensor, the output voltage increases with increasing CO₂ concentration, while the measurements from Runs 1, 2 and 3 show minimal dispersion. The carbon black-doped sensor follows a similar concentration-dependent trend, although slightly better dispersion is observed among its repeated measurements. These results indicate that both sensors provide reproducible responses, with some variation in the carbon black-doped sensor.

The measurements identify 2 wt.% carbon black-doped Eu₂O₃ as a promising composition for CO₂ detection under the fabrication and testing conditions used in this study. Its higher sensitivity, slightly improved linearity and lower reported resolution value are accompanied by good repeatability. The pure sensor exhibits lower absolute signal variation, emphasizing the need to consider response magnitude and signal consistency together when evaluating sensor performance.

Hysteresis studies: The hysteresis characteristics of the fabricated sensors were evaluated by comparing their output voltages during forward (increasing CO₂ concentration) and reverse (decreasing CO₂ concentration) measurement cycles. Hysteresis provides information about the reversibility of the sensing response and may be associated with adsorption-desorption processes at the sensor surface.

The pure Eu₂O₃ sensor exhibits a significant difference between the forward and reverse voltage responses as indicated by the separation of the trend lines (Fig. 10). This difference indicates hysteresis, with the sensor producing different output voltages at the same CO₂ concentration depending on the direction of measurement. Possible contributing factors include slow CO₂ desorption, incomplete recovery between exposure cycles and charge-transport limitations within the oxide sensing layer.

The 2 wt.% carbon black-doped Eu₂O₃ sensor exhibits a smaller difference between the forward and reverse responses, with the trend lines lying closer together. This behaviour indicates reduced hysteresis and improved reversibility under the tested conditions. The change may be related to the conductive pathways formed by carbon black, which can modify charge transport within the sensing layer. The more uniform

particle distribution observed by FESEM may contribute to more consistent gas-surface interactions. These factors could influence the adsorption-desorption response and the recovery of the electrical signal [24].

The comparison reveals lower hysteresis in the 2 wt.% carbon black-doped sensor than in the pure Eu₂O₃ sensor. The closer alignment of its forward and reverse responses supports improved response reversibility during changes in CO₂ concentration. These results, considered alongside the sensitivity, stability and repeatability measurements, provide further insight into the effect of carbon black incorporation on the gas sensing behaviour of Eu₂O₃ thick films.

Effect of doping concentration on resistance and NPN-PNP sensor behaviour: Table-4 summarizes the effect of carbon black concentration on the electrical resistance and sensing behaviour of Eu₂O₃-based sensors. The resistance decreases with increasing CB content, indicating enhanced charge transport within the composite sensing layer. The pure Eu₂O₃ sensor exhibits a high resistance of 11.4 GΩ. With the addition of 0.1, 0.5 and 1 wt.% CB, the resistance decreases to 10.5, 10.1 and 8.96 GΩ, respectively. A more pronounced reduction occurs at 2 wt.% carbon black, where the resistance reaches 2.97 GΩ. This change may be associated with improved interparticle connectivity and the formation of conductive pathways within the Eu₂O₃ matrix.

TABLE-4 EFFECT OF CARBON BLACK DOPING CONCENTRATION ON EUROPIUM OXIDE SENSOR RESISTANCE AND TYPE		
Europium oxide sensor	Resistance	Type
Pure	11.4 GΩ	N-Types
0.1% Carbon black	10.5 GΩ	N-Types
0.5% Carbon black	10.1 GΩ	N-Types
1.0% Carbon black	8.96 GΩ	N-Types
2.0% Carbon black	2.97 GΩ	N-Types
5.0% CB	1.42 kΩ	P-Types

At 5 wt.% carbon black, the resistance decreases further to 1.42 GΩ. This substantial reduction may indicate that a

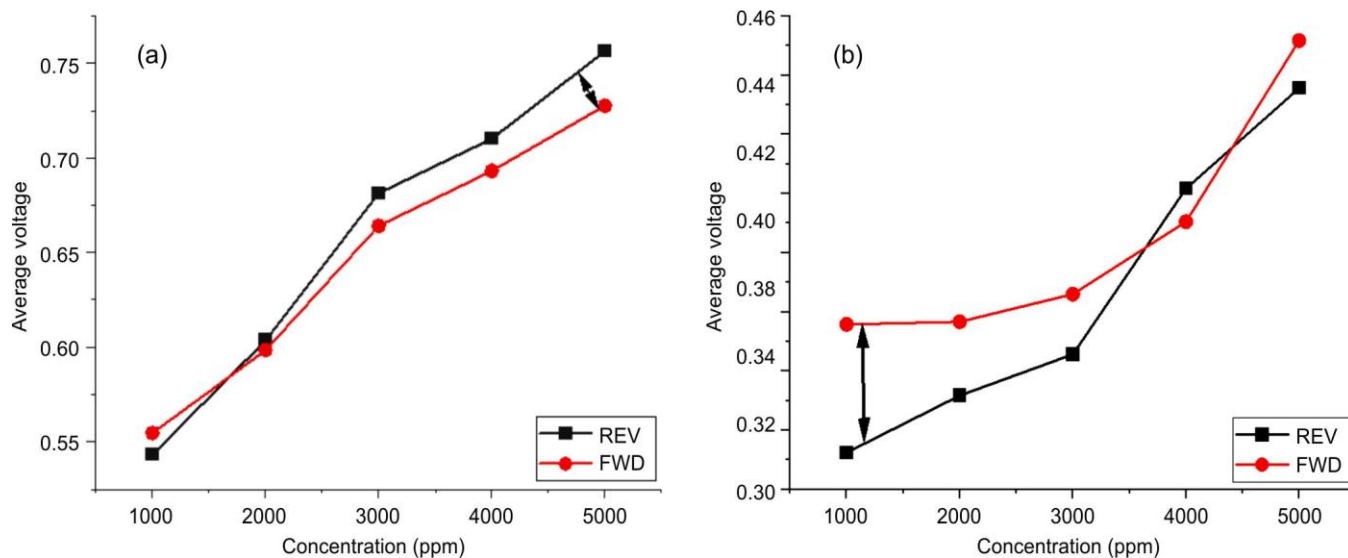


Fig. 10. Hysteresis curves of (a) 2 wt.% carbon black-doped Eu₂O₃ and (b) pure Eu₂O₃ sensors

continuous carbon-based conductive network has developed within the sensing layer, potentially reaching or exceeding the electrical percolation threshold. This resistance trend is consistent with the percolation behaviour reported for the carbon-filled composite materials [25,26]. At low carbon black concentrations, carbon particles may remain largely isolated within the Eu_2O_3 matrix, limiting charge transport and maintaining high resistance [25]. As the carbon black content increases, the separation between conductive particles decreases, allowing interconnected pathways to develop. Once a sufficiently continuous network forms, resistance can decrease sharply [26]. Similar behaviour has been reported in the carbon black-filled semiconductor and polymer composites, where small increases in filler concentration near the percolation threshold can cause substantial changes in electrical conductivity [14,25,26].

The sensing response remains n-type up to 2 wt.% carbon black, consistent with the n-type behaviour attributed to the Eu_2O_3 -based sensing layer in this study. At 5 wt.% CB, the response changes from n-type to p-type behaviour. This reversal may be associated with the increased contribution of the carbon phase to charge transport and interfacial interactions within the composite. The change in response polarity suggests that the dominant sensing mechanism is altered at the higher carbon black concentration.

The results show that carbon black incorporation reduces the resistance of the Eu_2O_3 sensing layer, with the highest decrease occurring at 5 wt.% CB, where the sensing response also changes polarity. The 2 wt.% carbon black-doped sensor provides a substantial reduction in resistance while retaining n-type sensing behaviour. This composition was selected for comparative analysis with the pure Eu_2O_3 sensor under the fabrication and testing conditions used in this study.

Comparison with previously reported CO_2 sensors:

The performance of the developed sensor was evaluated by comparing it with previously reported CO_2 sensors, as summarised in Table-5. The comparison considers operating temperature, CO_2 detection range and reported sensing performance metrics. Direct comparison of sensitivity values across different studies is difficult, as the sensors may operate through different sensing mechanisms and use different response definitions. Despite these differences, the comparison provides a useful benchmark for examining the performance of the proposed sensor in relation to existing CO_2 sensing technologies.

Conclusion

In this study, carbon black-doped europium oxide (Eu_2O_3) thick-film gas sensors were successfully fabricated and evaluated for room-temperature CO_2 sensing applications. The results demonstrated that the incorporation of carbon black significantly influenced the sensing performance of the Eu_2O_3 sensing layer. Among the investigated compositions, the 2 wt.% carbon black-doped sensor exhibited the best performance, achieving improved sensitivity, linearity, repeatability and reduced hysteresis compared to the pure Eu_2O_3 sensor. The enhanced sensing characteristics are attributed to the improved electrical conductivity, reduced particle agglomeration and enhanced interparticle connectivity introduced by carbon black incorporation. Electrical characterization showed a substantial decrease in sensor resistance with increasing carbon black concentration, which is consistent with the formation of conductive pathways. The change in sensing behaviour at higher carbon black loading further suggests that carbon black concentration influences charge transport within the composite. These findings support the potential of carbon black-modified Eu_2O_3 thick films for cost-effective and room temperature CO_2 monitoring.

TABLE-5
PERFORMANCE COMPARISON OF THE DEVELOPED CO_2 SENSOR WITH PREVIOUSLY REPORTED SENSORS

Morphology	Type	Material	Method	Temp. (°C)	Relative humidity	CO_2 (ppm)	Sensor response	Equation	Ref.
Thick film 2 μm	Resistive sensor	Copper(II) oxide	Spray pyrolysis	25	Not defined	100	3.5%	$S = \frac{I_g - I_a}{I_a} \times 100$	[27]
Thick film 2-5 μm with 10 wt.% LaCl_3	Impedance sensor	Lanthanum(III) chloride	Screen printing	400	Not defined	10,000	1.28	$S = \frac{R_g}{R_a}$	[28]
Thick film 2-5 μm with 10 wt.% La_2O_3	Impedance sensor	Lanthanum(III) oxide	Screen printing	400	Not defined	10,000	1.05	$S = \frac{R_g}{R_a}$	[28]
Thick film	Resistive sensor	Copper oxide, copper ferrite	Coprecipitation (paste)	350	Not defined	5000	10%	$S = \frac{R_g - R_a}{R_a} \times 100$	[29]
Thick film	Resistive sensor	Titanium dioxide	Screen printing	RT	Not defined	300 600 900	0.6 2.0 2.5	Not defined	[30]
Thick Film	Resistive sensor	Europium oxide	Screen printing	RT	Not defined	1000 2000 3000 4000 5000	0.00% Baseline 6.13% 11.46% 18.47% 19.73%	$S = \frac{V_g - V_a}{V_a} \times 100$	This work
Thick Film	Resistive sensor	Carbon black-doped europium oxide	Screen printing	RT	Not defined	1000 2000 3000 4000 5000	0.00 Baseline 11.10% 25.41% 30.70% 39.21%	$S = \frac{V_g - V_a}{V_a} \times 100$	This work

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language and no data, results or scientific conclusions were generated by AI. All analyses, interpretations and conclusions are the authors' own. The authors reviewed and edited the content and take full responsibility for the published work.

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