CeO₂ nano-hexagons decorated rGO/CNT heterostructure for high-performance LPG sensing

M. Sai Bhargava Reddy¹ · Saraswathi Kailasa¹ · B. Geeta Rani¹ · P. Munindra² · K. Bikshalu³ · K. Venkateswara Rao¹

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Abstract

This paper reports, the improved sensitivity and selectivity of liquefied petroleum gas (LPG) sensing at room temperature based on ternary heterostructure nanocomposite (CeO₂-rGO/CNT). Detection of LPG is required for proper environment monitoring to avoid any health hazards in the household and industrial areas. Towards this, a low-cost, high performance, and high stable room temperature gas sensor was fabricated. CeO₂ nanopuzzles was synthesized by Eggshell membrane template assisted hydrothermal method and nanocomposites by sono-chemical route. As-synthesized materials and nanocomposites were analyzed by employing characterizations like XRD, Raman, FT-IR, FESEM, and TEM, which confirmed the formation of shape, size, structure, and functional groups involved. The current study focuses on the fabrication of room temperature LPG sensor based on hybrid nanocomposites coated on flexible polyethylene terephthalate substrate working electrodes for In-house chemiresistive LPG detection unit to study response, stability, and selectivity parameters. The ternary heterostructure nanocomposite gas sensor exhibited good selectivity to LPG at room temperature. This sensor showed the response of 42% at 400 ppm of LPG, which is 2.21 times than pure CeO₂ sensor with a short response time 26 s and recovery time of 98 s, and gained 99% response after bending with 95.2% stability and 85.7% periodic stability of the sensor.

Keywords LPG · TEM · Raman · Chemiresistive · Heterostructure

1 Introduction

Electrical semiconducting properties of Metal oxides (MOs) invoke them suitable for sensing applications. Due to the striving intrinsic to high resistant values existing at low temperatures makes partially exploited their full potentiality [1]. The fabrication of different novel sensors through high response and low limit of detection (LOD) for gas sensing applications, adopting a conductive second phase, such as graphene and CNTs has turn into a

popular research area owned to its exceptional electric conductivity [2, 3], high surface to volume (S/V) ratio, and high mobility, outstanding mechanical properties like flexibility and elasticity [4]. It is substantial to identify the quantity of such second phases essential to get a sensible decrease in resistance. Considering their large S/V ratio, quite low thresholds were previously stated for MO-rGO/CNT nanocomposites [5]. Regardless the sensing response of rGO and CNTs is large and more rapid, though they get intensely distressed by relative humidity at room

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✉ K. Venkateswara Rao, kalagadda2003@gmail.com | ¹Center for Nanoscience and Technology, Institute of Science and Technology, JNT University, Hyderabad, Telangana 500085, India. ²School of Nanotechnology, Institute of Science and Technology, JNT University, Kakinada, Andhra Pradesh, 533003, India. ³Department of Electronics and Communication Engineering, Kakatiya University, Warangal, Telangana 506009, India.

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temperature, lower recovery, and poor selectivity, the limit of detection and repeatability that bounds their real-world application [6, 7].

An exciting concept that has fascinated a pile of interest to nanomaterial is the initiation of decorating rGO with as precursor and different MOs (MO-rGO NC). By altering, the degree of loading, resulting hybrid nanomaterials properties can be fine-tuned, as well as the NPs decorated on the rGO sheets [8]. Every single atom in graphene can interrelate with all target gas molecules. This phenomenon tunes them an ultra-sensitive material for gas sensing. The type of interactions between atoms and adsorbing gas molecules vary from weak Van der Waals interactions to strong covalent bonding, which leads to a drastic change in electrical conductivity [9]. The employment of CNTs as secondary materials in hybrid composite, where a MO is deposited on CNTs, deliver an easy diffusion for chemical gas accessing through over the bulk material and introducing identical open gas nano-channels hence, the achievement of a great surface to volume ratio, and providing good gas-adsorption sites due to inside and outside of MO-CNTs nanocomposites. [10, 11]. Gas sensing materials based on MO-rGO/CNTs established significant consideration due to their excellent properties towards detection of a vast range of gases, being greater response and working at lower temperatures, related with other gas sensors [12].

Development of thriving day-to-day applications of flexible sensors depending on nanoparticles (NPs) ranging from 1 to 100 nm are increasing [13]. Flexible sensors are projected to trigger the fabricating advanced, intelligent system sensing applications in printed electronics [14], medical management [15], gas and chemical sensors [16], environmental and medical sensors [17, 18], fitness monitoring, safety equipment, and sports [19]. This work is mainly focusing on fabricating low working temperature at small manufacturing costs with the high-performance gas sensors. Sensor working at lower temperatures is greatly appealing to offers low power consumption, as it simplifies the manufacturing of gas sensors [20].

LPG (liquefied petroleum gas) a odorless, colorless liquid which readily evaporates into gas and heavier than air also referred as a mixture of aliphatic hydrocarbons such as propane (C_3H_8) and butane (C_4H_{10}) as well as ethyl mercaptan (ethanethiol) in small amounts for odorization to detect leaks [21], which has most uses in cooking [22], Vehicle fuel [23], refrigerants [24]. Flammability limit of 1.8–8.8% LPG makes it explosive and have been poisoned due to inhalation and subsequently developed convulsion and reduced level of consciousness; hence, room temperature detection is preferable and operationally safe.

Rare earth oxides (REOs) or Lanthanide oxides, has recently been shown significant consideration for their well-known applications like ion-glass manufacturing,

gas and chemical sensors, microelectronics, and hydrogen storage [25–27]. The REO used in the present study, i.e., Cerium oxide (CeO_2). The attention of the present study is to adapt a hydrothermal process using eggshell membranes (ESM) as templates for synthesis of CeO_2 nanopuzzles and decorated on rGO and CNTs for (CeO_2 -rGO/CNT) hybrid material over gentle sonication [28, 29]. ESM are widely available bio-waste, low cost and eco-friendly materials have semipermeable structure. ESM have different functional groups, performs as a reducing agent during metal oxide nanoparticles synthesis. It is specified that the CeO_2 nanopuzzles falls in the nanometer scale and enhanced the surface area.

2 Experimental section

2.1 Synthesis of CeO_2 -rGO/CNT nanocomposite

The synthesis of CeO_2 -rGO/CNT nanocomposite includes two steps, the Process flow diagram for synthesis and experimental procedure were illustrated in the Fig. 1. Primary CeO_2 nanopuzzles have been prepared through ESM template assisted hydrothermal route, and secondary involves the decoration of CeO_2 nanoparticles on rGO sheets and CNTs. To obtain the CeO_2 nanopuzzles, 0.15 M $Ce(NO_3)_3 \cdot 6H_2O$ used as precursor and eggshells were collected from JNTUH Hostel. The inner membranes pulled out sensibly by hand, washed with DI water. 200 mg of dried ESM pieces (2 mm × 2 mm) were placed in the precursor solution for 24 h. In ESM: the huge availability of amino, carboxyl, and carbonyl functional groups [30] interrelates with the cerium ions. Uronic acid and saccharides comprise the aldehyde group (R-CHO) and performances as reducing agents to reduce the surface adsorbed Ce^{4+} into Ce^0 . The intermolecular and intramolecular forces, non-chemical effects, and electrostatic forces arrange the macromolecules, help for the formation of the nanoparticles, and control the shape [31]. In Hydrothermal route, the solution was taken into an autoclave and exposed to 180 °C for 24 h. After, the powder was washed with ethanol and DI water, dried then collect CeO_2 nanopowder. Finally, the collected sample was annealed at 800 °C to remove ESM derivatives and the FESEM image of Fig. 2d shows the CeO_2 nanoparticles were in the nanopuzzles shape.

Conversion of Graphite to Graphene Oxide by a modified Hummers method and morphology was illustrated in Fig. 2a clearly indicates the separated stacked layers of graphene oxide and in Fig. 2b confirms the complete formation of single-layered graphene by hydrothermal method (explained in ESI S2). In the next step, decoration of CeO_2 nanopuzzles on CNTs network displayed in Fig. 2c and rGO sheets through sonochemical route.

Fig. 1 Illustrates the process flow diagram for Synthesis and experimental procedure for CeO_2 -rGO/CNT hybrid ternary nanocomposite sensor

50 ml of ethanol was taken in a beaker, and CeO_2 NPs added under stirring for 30 min. Based on loading factor, CNT and rGO was added into the solution and continue the sonication using probe-sonicator for 3 h, to form CeO_2 -rGO/CNT hybrid ternary nanocomposite heterostructure, similarly binary NCs were also prepared.

3 Results and discussion

3.1 Characterization techniques

The crystal structure data of as-prepared CeO_2 -rGO/CNT

Fig. 2 shows the FESEM images of **a** GO; **b** rGO; **c** MWNTs; **d** CeO₂ nanopuzzles

ternary heterostructure nanocomposite was acknowledged by XRD, as shown in Fig. 3a. The XRD patterns of CeO₂, CeO₂-CNT, CeO₂-rGO, and CeO₂-rGO/CNT NC presented four main diffraction peaks with corresponding planes at 28.5° (111), 33°(200), 47.5° (220), and 56.3° (311), along with four minor peaks which represents the face-centered cubic CeO₂ (JCPDS 78-0694) [32]. The average crystallite size (D) of CeO₂, CeO₂-CNT, CeO₂-rGO, and CeO₂-rGO/CNT NCs estimated from full-width half maxima (β) using Scherrer's Eq. 1 [33, 34] and stated in the Table 1.

The diffraction peaks of CeO₂-CNT binary and CeO₂-rGO/CNT ternary NCs are increased, and CeO₂-rGO is slightly decreased indicating the crystalline structure of CNT and rGO support was well maintained in the NCs. Figure 3b shows the XRD patterns of (i) and (ii). MWNT and rGO peak at 26.4° and 26.49° with the corresponding plane (002), and insert shows the XRD pattern of GO.

The structural parameters calculated by using the below equations.

$$D = \frac{K\lambda}{\beta \cos \theta} \quad (1)$$

$$\varepsilon = \frac{\beta_{hkl}}{4 \tan \theta} \quad (2)$$

$$\delta = \frac{1}{D^2} \quad (3)$$

$$d = \frac{n\lambda}{2 \sin \theta} \quad (4)$$

Additional characterization of CeO₂-rGO/CNT NC was accomplished by Raman spectroscopy technique to analyze carbon-based materials. Raman spectra of CeO₂, CeO₂-CNT, CeO₂-rGO, and CeO₂-rGO/CNT were presented in Fig. 4a. A sturdy Raman band indicated one triply degenerate active band at 466 cm⁻¹ (F_{2g} band) for CeO₂ nanocrystal could be associated with the Ce-O bond, where Ce and O are eightfold, and fourfold coordinated in the CeO₂ fluorite structure [35]. The F_{2g} vibration mode is highly sensitive to the local change in bond length of oxygen-cation sublattice, which usually occurs during oxygen doping and the thermally induced non-stoichiometry effect. A blue shift (band shifted from 466 to 469 cm⁻¹) and redshift (from 466 to 465 cm⁻¹) consistent to the F_{2g} mode was indicated in the CeO₂-CNT and CeO₂-rGO Raman

Fig. 3 **a** XRD patterns of (i) CeO_2 ; (ii) CeO_2 -CNT; (iii) CeO_2 -rGO; (iv) CeO_2 -rGO/CNT hybrid nanocomposites, **b** XRD patterns of (i) MWNT; (ii) rGO (inset: GO)

Table 1 XRD crystal parameters

Samples	Crystallite size average (nm)	Strain (ϵ) $\times 10^{-3}$	Dislocation density (δ) nm	2 Theta ($^\circ$)	d-spacing ($\text{\AA}$)
CeO_2	37	2.623	0.001234	28.73	3.104
				33.20	2.695
				47.60	1.908
				56.58	1.625
CeO_2 -CNT	24	3.767	0.002235	28.64	3.113
				33.19	2.696
				47.59	1.909
				56.46	1.628
CeO_2 -rGO	27	1.608	0.001608	28.64	3.113
				33.13	2.701
				47.59	1.909
				56.46	1.628
CeO_2 -rGO/CNT	29	1.429	0.002853	28.60	3.118
				33.12	2.702
				47.54	1.910
				56.42	1.629

spectrum. A comparable blue shift ($466\text{--}467\text{ cm}^{-1}$) was perceived in the CeO_2 -rGO/CNT hybrid composite.

These shifts are the strong evidence of the charge transmission among CeO_2 and CNTs, and CeO_2 and rGO in order to evaluate the disordered structure of rGO and CNT in the hybrid nanocomposite. Clear evidence of D band ($\sim 1353\text{ cm}^{-1}$) and G band ($\sim 1593\text{ cm}^{-1}$) were observed in CeO_2 -CNT, CeO_2 -rGO, and CeO_2 -rGO/CNT. From I_D/I_G intensity ratio of CeO_2 -CNT binary (1.25) and CeO_2 -rGO binary (1.18), and CeO_2 -rGO/CNT ternary nanocomposite (1.33) were more disordered structures. Moreover, the I_D/I_G ratio of CeO_2 -rGO/CNT was greater to the binary NCs,

which can be credited to the drop of oxygen-consist of functional groups. Very little interpretations of Raman spectra exposed that the D and G bands of the binary and ternary NCs slightly shifted to a higher frequency, this may be due to various C-C bond length of CNT and C- CeO_2 .

To disclose the surface functional groups and the interaction between the three materials in the CeO_2 -rGO/CNT hybrid NC, FTIR analysis was observed. For the CeO_2 -CNT binary NC, the broad absorption band at 3410 cm^{-1} corresponded to O-H stretching. C-H asymmetric stretching of CNT at 2925 cm^{-1} , 2854 cm^{-1} (C-H symmetric stretching), 1603 cm^{-1} (C=O stretching), 1420 cm^{-1} (C=C stretching),

Fig. 4 **(a)** Raman spectra of (i). CeO₂, (ii). CeO₂-CNT, (iii). CeO₂-rGO, and (iv). CeO₂-rGO/CNT NCs, **(b)** FTIR spectra of (i). CeO₂, (ii). CeO₂-CNT, (iii). CeO₂-rGO, and (iv). CeO₂-rGO/CNT NCs hybrid nanocomposites respectively

1265 cm⁻¹ (O-H bending vibration), and 1080 cm⁻¹ (C-O stretching vibration) were observed with the observation of the Ce-O stretching peak at 511 cm⁻¹. The outcome gives enough evidence for the formation of CeO₂ NPs on CNTs and rGO. In the CeO₂-rGO/CNT ternary NC, skeletal vibration of C=C (558 cm⁻¹), and carbonyl (1724 cm⁻¹) disappeared for CeO₂ [36] as shown in Fig. 4b.

FESEM images of CeO₂-rGO/CNT NC clearly showed that the CeO₂ nanopuzzles structures break, turns into a hexagonal shape, and decorated on rGO and CNTs network in a nanocomposite shown in Fig. 5a, b.

As shown in Fig. 6a, b TEM images of CeO₂-rGO/CNT NC clearly indicating that nanopuzzles shape like CeO₂

nanoparticles was transformed into a hexagonal shape, which was encapsulated/coated, by rGO makes an interesting, unique morphology was steadily maintained. MWNTs with open ends were well distributed among the encapsulated CeO₂-rGO NC, which enhances its large availability of surface area makes it more suitable for gas sensing even at room temperature. Figure 6c illustrates the HRTEM image of the MWNTs diameter is about 8.9 nm, and the d-spacing value was 0.376 nm. SAED pattern of CeO₂-rGO/CNT ternary NC was observed (Fig. 6d) and were well-coordinated with XRD data.

Fig. 5 shows FESEM images of **a, b** CeO₂-rGO/CNT nanocomposite, (Fig. 4b inset: represents the CeO₂ hexagons, rGO Nano sheets and MWNT network in the nanocomposite)

Fig. 6 **a, b** Shows TEM images of CeO_2 hexagons decorated on rGO and MWNTs, **c** HRTEM image and **d** SAED pattern of CeO_2 -rGO/CNT NC

3.2 Dynamic response, response-recovery time studies

Gas sensing properties of CeO_2 nanopuzzles and CeO_2 -rGO/CNT nanocomposites were studied with different LPG concentrations at room temperature. To investigate the optimum LPG concentration, sensors were measured with LPG from 5 to 400 ppm. The resistance versus time (dynamic change in electrical resistance) was shown in Fig. 7a. The resistance of CeO_2 nanopuzzles decreased when LPG exposure and after increased and returned their original values upon exposure to dry air. The above observations showed that the CeO_2 sensor exhibits n-type semiconducting performance with steady sensing and recovery characteristics. All response time (T_{response})

and recovery times (T_{recovery}) of sensors to (5–400 ppm) LPG concentrations shown in Fig. 7b, abundant accessibility of free sites on sensor surface promotes to lower response time, on the other hand, higher in recovery time as a result of decreased rate of desorption relative species. The dynamic response and response-recovery time values of CeO_2 , CeO_2 -CNT, CeO_2 -rGO, and CeO_2 -rGO/CNT hybrid nanosensors were presented in Table 2.

The dynamic response data of flexible CeO_2 and CeO_2 -rGO/CNT sensor to 5–400 ppm concentration of Liquid Petroleum Gas (LPG) room temperature working, as illustrated in Fig. 8. The dynamic response figure shows a rise in the LPG gas concentration advances the response growth. Besides, CeO_2 -rGO/CNT flexible sensor in response to low (10-ppm) adsorption with

Fig. 7 **a** Dynamic change in electrical resistance, and **b** Response and recovery time of (i). CeO₂, (ii). CeO₂-CNT, (iii). CeO₂-rGO and (iv). CeO₂-rGO/CNT hybrid sensors

Table 2 Comparison of recent LPG sensing literature with this work

Sensor material	Response (%)	Response time (s)	Recovery time (s)	Concentration (ppm)/working temperature (°C)	References
Polyaniline/titania	43.2	76	95	0.4 vol%/RT	[38]
CdO	20	18	32	10 vol%/RT	[39]
Ni _{0.8} Co _{0.2} Fe ₂ O ₄	70	40	60	1000/250	[40]
20 wt% ethylene glycol-doped PEDOT-PSS	92	8.45	12.75	2400/RT	[41]
PANI	1.39	23	152	3000/RT	[42]
PANI/MgO (30%)	1.82	19	70		
PANI/MgO (40%)	1.95	11	60		
Ce-doped SnO ₂	89.2	7	9	500/300	[43]
WO ₃ -PEDOT: PSS/Ag	1.3	29.4	54	500/RT	[44]
CeO ₂	19	54	34	400/RT	This work
CeO ₂ -CNT	22	44	55	400/RT	This work
CeO ₂ -RGO	27	58	62	400/RT	This work
CeO ₂ -RGO/CNT	42	26	98	400/RT	This work

5% response. At greater adsorption of LPG (400-ppm) sensor exhibited the highest response 2.21 times than pure CeO₂ sensor, besides with short response time. The high concentration of LPG gas molecules involve in redox reactions promotes growth in response. CeO₂, CeO₂-CNT, and CeO₂-rGO hybrid flexible sensors response was also shown. The response of CeO₂-rGO is

21% higher than CeO₂-CNT sensors because, rGO provides a large effective surface area of increased conductivity, compared with the case of CNTs when addition to CeO₂.

Fig. 8 Dynamic response plot of (i). CeO₂, (ii). CeO₂-CNT, (iii). CeO₂-rGO, and (iv). CeO₂-rGO/CNT hybrid sensors

3.3 Stability and selectivity studies

Figure 9b displays the periodic stability is about 85.7% of CeO₂-rGO/CNT hybrid sensor to 400 ppm LPG for 30 days. As observed that the stability of sensor shown, after 15 days sensitivity of the sensor slowly decreases from 42 to 39 and 36% after 30 days, revealing better stability of the CeO₂-rGO/CNT hybrid sensor. Simultaneously response properties of CeO₂-rGO/CNT hybrid flexible sensor at the time of bending was noted and displayed in Fig. 9a. Observed data of the flexible sensor are 42%, and 40% upon a flat, bending of 3 cm radius respectively. A small reduction in response was observed when bending, but after it is regained > 99% response when reached original position, signifying that the outstanding reproducibility of the sensor. The repeatability of CeO₂-rGO/CNT hybrid flexible sensor upon 10,000 s shown in Fig. 9c, shows better cyclic stability.

Fig. 9 **a** Response properties of CeO₂-rGO/CNT hybrid flexible sensor upon bending, **b** Long-term stability performance (reproducibility), **c** The repeatability of CeO₂-rGO/CNT hybrid flexible sensor upon 10,000 s, **d** Selectivity study

Selectivity, is the competence of a sensor responds to a specific chemical species in relative to other species, is referred as a significant gas sensing parameter. Various target gases were employed for the selectivity process of CeO₂-rGO/CNT hybrid sensor. The selectivity bar chart of CeO₂-rGO/CNT hybrid sensor towards Methanol, NO₂, Acetone, Ethanol, Formaldehyde, Isopropanol, Toluene, and H₂ gas was shown in Fig. 9d. As described CeO₂-rGO/CNT hybrid sensor showed the higher response of 42% to 400 ppm of LPG gas related to added gases, being robust interactions among vigorous sensing of CeO₂-rGO/CNT, because LPG molecules tend to consumption of more oxygen. The selectivity factor (K) of LPG indifference to test gases was intended by $K = \frac{S_a}{S_b}$, and detected results are depicted in Table 3. Here in S_a is sensor response towards LPG and S_b is sensor response to different test gases. The greater the K value exposes that the sensor has exceptional capability towards particular analyte from the surrounding.

3.4 LPG sensing mechanism

The Ionosorption model is a Chemisorption process widely used to understand the sensing mechanism on semiconductor surfaces. In n-type semiconductor metal oxide nanostructures (SMONs), ambient oxygen adsorbs on n-type SMON and taking an electron from the conduction band (CB), because of its high electron affinity to generate ionized oxygen anions and producing a depletion layer, causes band bending forms a potential barrier. At room temperature (< 373 K) superoxide anions (O₂⁻) species was formed, possibly dissociated and bound to the surface through an unoccupied chemisorption site for oxygen in various forms while extracting electrons from the semiconductor to ionize the chemisorbed oxygen.

Room temperature reactions were represented as below:

As shown in Fig. 10 Establishing electrical core-shell layers by adsorbing oxygen in n-type CeO₂ semiconductor shows a significant change in conductive behavior. The shell-to-shell relations made among the particles in CeO₂ mainly determines the sensor resistance of n-type CeO₂. Superoxide anions (O₂⁻) used to oxidize the reducing gas (LPG), and the remnant electrons were injected into

CeO₂ core, that reduces the resistance of sensor related to the analyte (LPG) concentration and increases density of charge carriers. Modification of surface and implementation of surface defects and interfaces like the introduction of heterojunctions and vacancies affect the gas sensor performance. Totalling of rGO and CNTs on metal oxides can considerably progress their conductivity and improve their response at room temperature.

In gas sensing, the LPG molecules interact with superoxide anions, a series of reactions take place; finally, H₂O and CO₂ are coming out as a bi-products.

where C_nH_{2n+2} indicate the different chemical compounds with n = 1, 2, 3 and 4 such as CH₄, C₃H₈, and C₄H₁₀, etc.

In the fabricated CeO₂-rGO/CNT sensor, the surface of the rGO and CNTs are greatly available for the adsorption of O₂ molecules. Hence, when CeO₂-rGO/CNT sensor exposed to air, O₂ molecules can simply be adsorbed on the surfaces of CeO₂, rGO sheets, and CNT network traps electrons from the CB of CeO₂-rGO/CNT ternary NC, helping the growth of depletion layers on the surface of hybrid NC and formed the heterojunction interface. The presence of these multiple depletion layers significantly drops the free charge carriers from rGO and CNTs, making the CeO₂-rGO/CNT sensor is more resistive associated with the pure CeO₂ sensor. When CeO₂-rGO/CNT sensor open to LPG, the LPG molecules react with O₂⁻ on the surface CeO₂-rGO/CNT and delivers largely confined electrons (i.e., the existence of multiple depletion layers) related to Pure CeO₂ sensor, which greatly influences the descent in resistance.

Response (R) of a semiconducting gas sensor measured by determining the change in electrical resistance of the sensor because of the interface between the analyte gas and the metal oxide surface [37]. The response of SMONs sensor is calculated using Eq. 9.

$$\text{Response (\%)} = \left(\frac{|R_a - R_g|}{R_a} \right) * 100. \quad (9)$$

Table 3 Selectivity factor (K) of CeO₂-rGO/CNT ternary hybrid nanocomposite sensor with LPG as a target gas

Analyte gas	H ₂	Toulene	NO ₂	Isopropanol	Formaldehyde	Ethanol	Acetone	Methanol
K	21.55	13.58	6.09	6.5	5.22	8.42	7.32	3.84

Fig. 10 LPG sensing mechanism

4 Conclusion

In this experimental work, CeO_2 nanopuzzles and GO successfully synthesized through ESM template assisted hydrothermal route and modified Hummers method. As-synthesized CeO_2 nanostructures decorated on rGO and CNT networks by physical mixing (sonication). Structural analysis proved the existence of CeO_2 , rGO, and MWNTs, and morphology confirmed the existence of CeO_2 hexagons well decorated on rGO sheets and CNT network. The prepared CeO_2 -rGO/CNT ternary heterostructure nanocomposite coated on flexible PET substrate by simple spin-coating technique and used for the sensing of LPG at 27 °C. Gas sensor based on Chemiresistive model provides the information about CeO_2 -rGO/CNT sensor showed the good selectivity to liquefied petroleum gas

(LPG) at room temperature gives a response 2.21 times than pure CeO_2 sensor at 400 ppm of LPG with a short response, recovery time and gained ~ 99% response after bending with good stability of the sensor. Therefore, we conclude CeO_2 decorated on rGO and CNTs will act as an ecofriendly and low-cost room temperature chemiresistive flexible LPG gas sensing device.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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