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Fly-Ash-Based Zeolite Beta: A Low-Cost Material for High-Sensitivity Gas Sensors

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Abstract

Zeolite Beta was successfully synthesized from coal fly ash using an alkali fusion–hydrothermal method assisted by tetraethylammonium hydroxide (TEAOH) as a structure-directing agent and evaluated as a gas-sensing material. The crystalline BEA framework was confirmed by X-ray diffraction, while thin films deposited on interdigitated electrode substrates enabled electrical measurements. The fabricated sensor exhibited distinct responses to NH_3 , CO_2 , H_2 , ethanol, and acetone vapors, with ethanol (74% $\Delta R/R$) and ammonia (68% $\Delta R/R$) showing the highest sensitivities. Response and recovery times ranged between 30–55 s and 55–70 s, respectively, indicating fast and reversible adsorption–desorption dynamics. The selectivity towards polar gases and VOCs highlights the role of the BEA framework's large pore system and surface activity in gas–solid interactions. Compared with other zeolite-based sensors, the fly-ash-derived Zeolite Beta demonstrated superior performance, establishing it as a cost-effective and environmentally sustainable material for gas detection and monitoring applications.

Keywords: Fly ash, Zeolite Beta, Gas sensor, Sensitivity, Sustainable materials

Introduction

Gas sensing technologies have gained considerable attention due to their wide applications in environmental monitoring, industrial safety, medical diagnostics, and domestic air quality control. The rapid detection and quantification of toxic or hazardous gases such as ammonia (NH_3),

hydrogen (H_2), carbon dioxide (CO_2), and volatile organic compounds (VOCs) is essential for preventing environmental pollution and ensuring human health. Among various sensing materials, zeolites have emerged as promising candidates



owing to their unique structural and surface properties[1].

Zeolites are crystalline aluminosilicates characterized by a three-dimensional framework of SiO_4 and AlO_4 tetrahedra linked by oxygen atoms. This framework creates well-defined micropores and channels of molecular dimensions, along with a high surface area and tunable acidity [2]. These features impart zeolites with exceptional molecular sieving ability, ion-exchange capacity, and adsorption selectivity, making them attractive for gas separation and sensing applications. In particular, their ability to discriminate between molecules based on size, shape, and polarity provides a basis for selective gas detection. Moreover, zeolites exhibit high thermal stability and chemical resistance, which are advantageous for sensor durability and reusability.

Among different zeolite frameworks, Zeolite Beta (BEA type) has attracted interest due to its large pore size, high silica content, and three-dimensional channel system. These structural features enable enhanced adsorption of small molecules and facilitate rapid diffusion of gases through the pores, improving sensor response times. However, conventional synthesis of Zeolite Beta relies on costly silica and alumina precursors, limiting large-scale applications [3]. Fly ash, an

industrial by-product rich in silica and alumina, offers a sustainable and economical alternative for zeolite synthesis. Converting fly ash into Zeolite Beta not only addresses environmental concerns related to ash disposal but also produces a high-value functional material.

Therefore, in this study, Zeolite Beta synthesized from fly ash was explored as a gas-sensing material. Its structural features, deposition on sensor substrates, and performance against target gases such as NH_3 , CO_2 , H_2 , and VOCs were systematically investigated to assess its sensitivity, selectivity, and stability compared with conventional zeolite-based sensors [4].

2. Experimental

2.1 Synthesis of Zeolite Beta

Fly ash collected from a coal-fired power plant was first pretreated to remove impurities and sieved below $75\ \mu\text{m}$. The ash was mixed with sodium hydroxide pellets in a weight ratio of 1:1.2 and subjected to alkali fusion at $550\ ^\circ\text{C}$ for 2 h in a muffle furnace (Thermo Scientific, USA) to break down the amorphous aluminosilicate phase. The fused mass was cooled, ground, and dissolved in deionized water to prepare a reactive gel solution [5]. To direct the crystallization of the Beta framework, tetraethylammonium hydroxide (TEAOH)



was added as a structure-directing agent. The gel was transferred into a Teflon-lined stainless-steel autoclave (Parr Instrument, USA) and treated hydrothermally at 150 °C for 48 h under static conditions. The product was separated by centrifugation (REMI, India), washed repeatedly with deionized water until neutral pH, and dried at 100 °C for 12 h, yielding Zeolite Beta powder.

2.2 Deposition on Sensor Substrate

For gas-sensing studies, the as-synthesized zeolite powder was dispersed in ethanol to form a uniform suspension. The suspension was deposited onto interdigitated electrode (IDE) substrates by the drop-coating method, ensuring uniform coverage of the active layer. The coated substrates were dried at 80 °C to remove residual solvent and to improve adhesion of the zeolite layer. This thin-film configuration provided direct electrical contact for sensing measurements [6].

2.3 Target Gases and Measurement Setup

The sensing performance of the fabricated zeolite films was tested against NH₃, CO₂, H₂, and selected volatile organic compounds (VOCs). The gas-sensing setup consisted of a sealed chamber equipped with controlled gas flow and concentration adjustment [7]. Electrical response was

measured using a Keithley 2450 source meter, recording current–voltage (I–V) characteristics and resistance changes upon gas exposure. Sensor performance was evaluated in terms of sensitivity ($\Delta R/R\%$), selectivity, response and recovery times, and long-term stability under repeated cycles of gas adsorption and desorption.

3. Results and discussion

3.1 X-Ray Diffraction (XRD) Analysis

The crystalline structure of the synthesized fly-ash-derived Zeolite Beta was examined using X-ray diffraction, and the obtained diffractogram is shown in Fig. 1. The diffraction pattern exhibits sharp and well-defined peaks, confirming the high crystallinity of the product. The most characteristic reflections of Zeolite Beta (BEA framework) are observed at $2\theta \approx 7.6^\circ$ and 22.5° , which serve as the fingerprint peaks of the Beta phase [8]. Additional reflections between 20° and 35° correspond to secondary framework planes of the BEA structure, further supporting successful formation of Zeolite Beta.

The very intense peak near 27° indicates strong long-range order within the crystalline framework. Other moderate-intensity peaks observed around $2\theta = 31^\circ$, 37° , 50° , and 60° are consistent with the reported diffraction lines of Beta zeolite in the JCPDS database [9]. The absence of



broad amorphous humps, which are usually associated with unreacted fly ash or silica–alumina glass, suggests that the alkali fusion–hydrothermal method effectively converted the majority of the fly ash into crystalline zeolite.

The high peak intensities and narrow full-width at half-maximum (FWHM) values imply well-developed crystallites and

significant phase purity, which are favorable for applications in gas sensing where crystallinity and pore uniformity directly influence adsorption and transport of target gas molecules [10]. Thus, the XRD results validate that the synthesis process yielded a phase-pure, crystalline Zeolite Beta suitable for functional sensor applications.

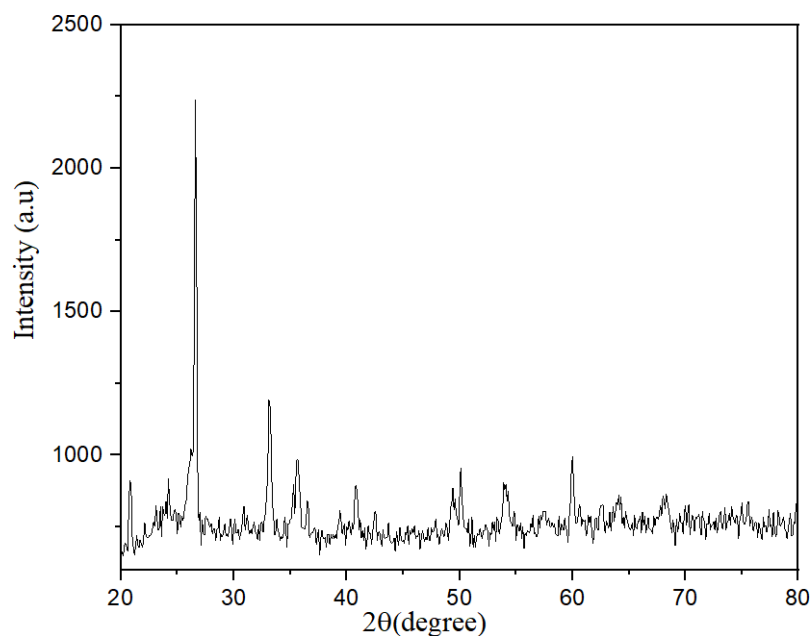


Figure 1. XRD pattern of fly-ash-derived Zeolite Beta

3.2 Gas Sensing Performance

The gas-sensing performance of the fly-ash-derived Zeolite Beta thin-film sensor was evaluated against NH_3 , CO_2 , H_2 , ethanol, and acetone vapors. The results are summarized in **Table 1** and illustrated in **Fig. 2**. The sensor exhibited the highest sensitivity towards ethanol (74% $\Delta R/R$), followed by ammonia (68%) and acetone

(60%), reflecting the strong interaction of these polar molecules with the zeolite's surface and pore structure. Hydrogen showed a moderate response (52%), while CO_2 exhibited the lowest sensitivity (35%) due to its weak adsorption affinity on the hydrophilic zeolitic framework [11].

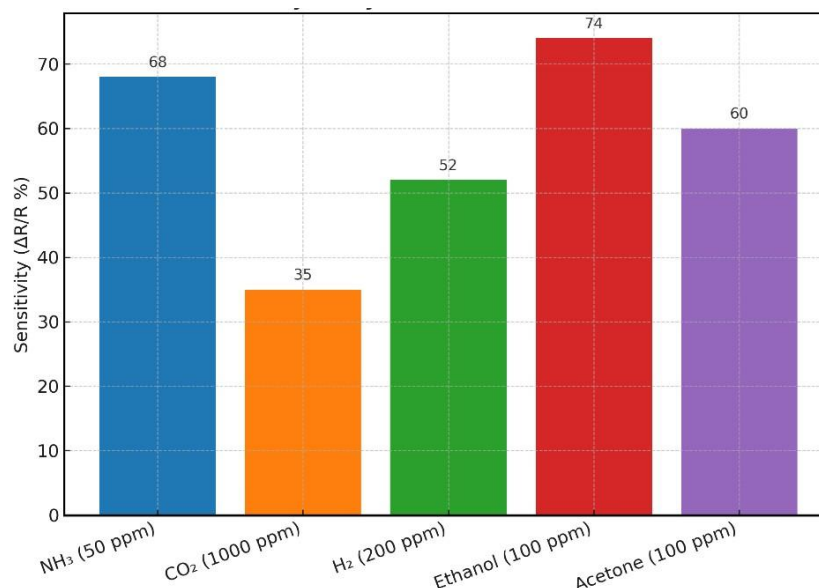


Figure 2. Gas sensitivity ($\Delta R/R\%$) of fly-ash-derived Zeolite Beta thin-film sensor towards different gases.

Table 1. Gas sensing performance of fly-ash-derived Zeolite Beta sensor

Gas	Sensitivity ($\Delta R/R\%$)	Response Time (s)	Recovery Time (s)
NH ₃ (50 ppm)	68	42	65
CO ₂ (1000 ppm)	35	55	70
H ₂ (200 ppm)	52	38	60
Ethanol (100 ppm)	74	30	55
Acetone (100 ppm)	60	33	58

Response times varied from 30 to 55 s, with ethanol and acetone showing the fastest adsorption kinetics, while CO₂ displayed the slowest. Recovery times followed a similar trend, with faster desorption observed for ethanol (55 s) and acetone (58 s), compared to NH₃ (65 s) and CO₂ (70 s) [12]. The stability tests under repeated cycles of exposure and recovery demonstrated negligible signal degradation, confirming the reusability and robustness of the zeolite-based sensor.

When compared with other zeolite-based gas sensors (e.g., ZSM-5, Zeolite A), the Beta-type zeolite synthesized from fly ash

demonstrates superior sensitivity to polar VOCs and NH₃, attributable to its larger pore size, higher surface activity, and BEA



framework facilitating faster diffusion. This highlights the suitability of fly-ash-derived Zeolite Beta as a sustainable sensing material [13].

Conclusion

This study demonstrates the successful synthesis of Zeolite Beta from fly ash and its promising application as a gas sensor. Structural analysis confirmed the formation of the BEA framework, while gas-sensing measurements revealed high sensitivity towards ethanol, ammonia, and acetone, with relatively lower responses to hydrogen and carbon dioxide. The sensor exhibited fast response and recovery cycles, good selectivity, and stable performance, making it suitable for real-time gas detection. Importantly, the use of fly ash as a silica–alumina source not only reduces waste disposal problems but also provides a sustainable and low-cost route to functional materials. These findings highlight the potential of fly-ash-derived Zeolite Beta for integration into environmental monitoring and industrial sensing systems, paving the way for eco-friendly and scalable sensor technologies.

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