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Advances in Carbon-Based Materials for Printed Gas Sensors: A Comprehensive Review

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Abstract: *Industrial expansion and rapid population growth have significantly increased the need for effective detection of harmful gases and volatile organic compounds (VOCs). This has driven growing interest in developing gas sensors that are not only low-cost and disposable but also suitable for wearable applications. In this context, carbon-based materials have emerged as promising sensing elements due to their adaptable physical and chemical properties when exposed to different gases. This review presents an overview of printed gas sensors that utilize carbon allotropes such as carbon nanotubes, graphene, and carbon black as active sensing layers. It discusses their fabrication using various printing methods on both rigid and flexible substrates. Key factors influencing sensor performance—such as ink composition, choice of printing technique, substrate type, number of printing layers, and surface functionalization—are critically examined. Additionally, the review highlights strategies that involve combining carbon materials with metals or polymers to improve sensitivity, selectivity, and overall sensor performance. Finally, it outlines current challenges and explores future directions in the development of cost-effective, wearable, and disposable gas sensors, aiming for efficient and sustainable real-time monitoring of hazardous gases.*

Keywords: Industrial expansion and rapid population growth have significantly increased the need for effective detection of harmful gases and volatile organic compounds (VOCs).

I. INTRODUCTION

The adverse effects of industrialization and increased population (S. Lee et.al, P.K. Panigrahi et. al.)] have raised the requirement for the detection of several harmful gases such as nitrogen dioxide (NO2), ammonia (NH3), hydrogen sulfide (H2S), and volatile organic compounds (VOCs). In this context, gas sensors have garnered substantial research attention because of their critical role in diverse sectors such as medical diagnostics (J. Wang et al.), food industry N.M. Shaalan et. al., agriculture (D. Suriano et. al), environmental monitoring (S. Dhall, B.R et. al.), and public safety (G. Jiang, et al) [7]. Gas sensors are used for breath analysis in medical diagnostics, whereas in the food industry, they are used to evaluate the freshness of food by sensing the gases released from the spoiled food (K. Timsorn et. al). Further, in industrial applications, the risk of gas leakage during manufacturing and transportation requires real-time monitoring to ensure public safety(H. Wan et.al.). As a result, gas sensors play a pivotal role in health and safety. The gas sensors market in 2025 is about 1.69 billion USD and is projected to reach 2.77 billion USD by 2030, at a compound annual growth percentage of 10.42 (B. V. Jadhav et. al.). This growth highlights the rising demand for gas sensors across various areas. Considering its importance in various fields, diverse types of gas sensors are reported which mainly include field effect transistor Chemoresistive, electrochemical, surface acoustic wave, optical and calorimetric (Q. Zou et. al). Traditional fabrication techniques for manufacturing these gas sensors include lithography, chemical vapor deposition (CVD), and atomic layer deposition, utilize high temperatures and vacuum, which can be incompatible with flexible substrates.

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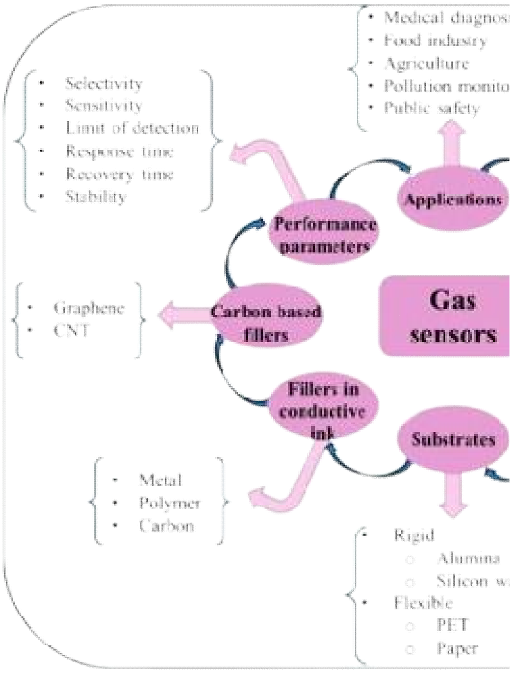

Fig. 1. Schematic representation of various aspects

Moreover, due to the advancement in digital health care for detecting chemical signals from the human body and identifying harmful gases in the surrounding environment, wearable sensors are in great demand. For manufacturing these compact, real-time monitoring sensors, flexible substrates are commonly used, which allow them to be comfortably worn or integrated into clothing and accessories. In this context, printing methods enable deposition of functional ink on a wide array of substrates, including both flexible and rigid, unlike traditional techniques (A. Nijkoops, et al). Printing also allows large-scale controlled manufacturing of low-cost miniaturized sensors for pressure, temperature and gas sensing applications (M. Serafini, et al). With the need for real-time monitoring, miniaturization, portability, flexibility, and low power consumption of these sensors are very beneficial and essential (H. Zhu, et al). This can be achieved by the fabrication of sensors with certain advanced materials that possess specific properties. Metal oxide semiconductors (MOS) as an active layer in gas sensing applications have been widely explored due to their capability to change electrical properties in the presence of gas molecules (RD Prakshale et. al). ZnO, SnO2, CuO, In2O3, WO3, etc., are some of the MOS reported for gas sensing applications. But the high operating temperatures that can often rise to 600 ◦C due to the slow desorption and need for frequent recalibration limit their applications on flexible substrates including plastic and paper that cannot withstand such high temperatures. MOS sensors also show poor selectivity in the presence of various gas mixtures.

II. OVERVIEW SUMMARY

The present review attempts to provide a comprehensive overview on the performance of carbon-based materials and their composites as printed gas sensors. These sensors find applications across diverse areas, ranging from breath analysis and food freshness monitoring to industrial safety. The review highlights the advantages of printing techniques over conventional sensor fabrication methods such as i) low fabrication cost as it requires less material and fewer processing steps, thereby reducing overall production costs, ii) enables scalability and mass production, iii) allows deposition of diverse materials on a wide variety of substrates, iv) facilitates design flexibility through patterning of complex or customized sensor geometries without expensive lithography, v) compatibility with flexible and wearable substrates such as plastics, textiles, or paper, unlike rigid wafer-based methods, vi) less waste and vii) RT processing. Further, the article also compares different printing approaches used in gas sensor development. Inkjet printing provides high resolution, fine patterns, and research-scale prototyping, whereas screen and dispense printing facilitates development of thick films and lab-scale fabrication. Limited viscosity range of ink, nozzle clogging risks and slow large-area production are the limitations of gas sensor fabrication through inkjet printing. Lower resolution and less suitability for producing fine and complex patterns are the disadvantages of screen printing compared to inkjet. The present article also examines the advantages and disadvantages of various sensing materials used in the preparation of gas sensors such as metal oxides, polymers, carbon materials and their hybrids with more emphasis on carbon-based materials like graphene and CNT. Each ink formulation is customized for specific printing methods such as inkjet, screen, aerosol jet, electrospray along with the type of gas (NH3, NO2, VOCs, ethanol, CH2O, CO2 and so on) to be sensed. This review also gives an insight into how performance parameters like sensor response, sensitivity, selectivity, limit of detection, response and recovery times vary depending on the ink composition, printing technique, choice of substrate and the target gas. The inkjet printed sensors demonstrated the lowest detection limits, reaching the ppt range, outperforming other printing techniques. Meanwhile, screen printed sensors exhibited modTable erate sensitivity but is cost-effective and mass producible. Overall, this review emphasizes the advances in printing technologies and ink formulations for creating low-cost, ecofriendly, high-performance sensors that operate efficiently, often at RT, and are adaptable to real-world applications.

III. LIMITATIONS AND FUTURE SCOPE

Printed carbon-based gas sensors, while offering several attractive features for low-cost real-time monitoring of gases, also present certain limitations. In real-world applications, these sensors operate in environments containing mixtures of gases; therefore, achieving selectivity toward a specific target gas remains a major challenge. To enhance selectivity, it is required to functionalize these carbon materials. Further, they also pose challenges due to their interference with other environmental factors including humidity, which can alter the sensor response and stability. Printing enables the fabrication of sensors on both flexible and rigid substrates, offering several advantages such as reduced production cost, less wastage, and low power consumption. However, reproducibility of these sensors must be considered, as proper ink formulations, printing resolution, film thickness, and film uniformity will affect the sensing process. Even though these carbon-based gas sensors can operate at RT, to recover to the original baseline values, sometimes it requires additional heat treatment for the complete desorption of gas molecules. Though it is not possible to meet all the demands of an ideal sensor in one device, future attempts should focus on improving its selectivity by combining it with novel metal oxides or polymers to combine the properties of different materials. Reducing the recovery time without the aid of any heat sources can further help in its integration with wearables. Future studies can also include tailoring the ink formulation to enhance sensitivity and selectivity without compromising the electrical conductivity. Further, integration of these sensors with machine learning and artificial intelligence can be of major advantage in real-time detection.

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