Carbon-based flexible gas sensors: an overview of current trends

M. A. Costa Angeli[1], L. Petti[1], P. Lugli[1]

[1] *Faculty of Science and Technology, Free University of Bozen-Bolzano, Italy*

Corresponding author: M. A. Costa Angeli
Contact information: MartinaAurora.CostaAngeli@unibz.it

Gas sensors are attracting high interest because of their widespread in industrial applications for environmental monitoring and gas leakage detection, but also in the new avenues of precision agriculture, smart packaging for the detection of food spoilage, and wearable applications for human health monitoring. The actual market of gas sensors is dominated by silicon-based metal-oxide devices, which still show some challenges in terms of power consumption, reliability, and selectivity. Beyond these performance metrics, modern applications demand low-cost flexible sensors that can operate at room temperature. Thus, during the last decade, the attention moved towards other gas-sensitive materials, such as conductive polymers and carbon-based materials, e.g. carbon nanotubes (CNTs), carbon black, and graphene. Among all, carbon based-nanomaterials, due to the extremely high surface-to-volume ratio that is ideal for gas molecules adsorption, have attracted particular interest thanks to their capability to detect several gases (NH_3, NO_2, H_2O, C_6H_6, ethanol, etc.) at room temperature with high sensitivity. Moreover, these sensitive materials can be deposited and pattered through additive manufacturing techniques, as inkjet printing, screen printing, 3D printing enabling the large-scale fabrication of low cost-effective systems and the employment of flexible substrates, such as polymeric sheets, textiles, and also environmental-friendly paper foils [1], [2]. Thus, the recent advancements in both nanostructured materials and functional printing offered new opportunities and flexibility in the manufacturing of gas sensors. In this context, the recent literature showed an increasing number of works focused on optimizing flexible carbon-based gas sensors to achieve a high selectivity towards the target analyte, fast response and recovery time and, good repeatability and stability.

Although carbon-based materials were revealed to be sensitive toward many gases, they showed limitations in selectivity and recovery. Indeed, it is worth noting that gas molecules cannot be completely desorbed at room temperature, resulting in poor stability and long recovery time of carbon-based gas sensors. Several methods have been extensively explored to improve the desorption of the residual molecules: a common strategy is to integrate an auxiliary device to externally heat or UV-irradiate the sensor to increase the desorption rate of the trapped molecules or to perform a self-recovery by applying a relatively high (5 V) DC voltage to the sensors itself [3], [4].

The improvement of sensor selectivity is another extensive research topic of carbon-based gas sensors. Indeed, carbon-based nanomaterials can indistinctively detect all the molecules that have enough binding energies and charge transfers with the nanotubes. Thus, several approaches have been proposed to improve the sensor sensitivity such as the nanomaterial functionalization (e.g. -COOH) and biofunctionalization (e.g. DNA), the employment of CNTs/conductive polymer composite (e.g PANI, PEDOT: PSS), the doping with metal (Pt, Cu, Au) and metal oxide (Co_3O_4, SnO_2, Fe_3O) nanoparticles [5]–[8]. Another way to address the issue of selectivity is the employment of algorithms, such as principal component analysis, and machine learning, able to analyze the behavior of the sensor, and discriminate the measured analytes [9], [10]. Moreover, this latter strategy can optimize the resources of computation, making feasible the future development of a smart sensor, crucial for the development of the Internet of Things.

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