The Sensing Techniques for Formaldehyde Detection

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Contributor: Yuru Min , Chenyao Yuan , Donglei Fu , Jingquan Liu

Formaldehyde has been regarded as a common indoor pollutant and does great harm to human health, which has caused the relevant departments to pay attention to its accurate detection. Spectrophotometry, gas chromatography, liquid chromatography, and other methods have been proposed for formaldehyde detection. Among them, the gas sensor is especially suitable for common gaseous formaldehyde detection with the fastest response speed and the highest sensitivity.

formaldehyde detection gas sensor polymer

1. Introduction

In society nowadays, the majority of human production and living activities are carried out indoors; that is, modern people usually spend 80–90% of their time indoors [1]. People's physical and mental health is directly affected by indoor air quality [1][2][3]. At present, more than 400 types of indoor pollutants have been identified, which is far more than human expectations [4][5][6]. Volatile organic compounds (VOC) are common indoor air pollutants and have a great impact on human health [7][8][9]. When the indoor concentration of VOC reaches a certain level, it will cause nausea, dizziness, vomiting, etc., in a short time, and even coma in a severe case [10][11][12].

Formaldehyde has penetrated all aspects of human production and life as a common VOC, which plays a significant role in the chemical industry, textile industry, anti-corrosion, and even cosmetics [13][14][15][16][17]. For ordinary families, indoor formaldehyde pollution mainly comes from indoor decoration [18]. For example, the main component of most adhesives used in artificial panels and furniture is formaldehyde [19]. In addition, the paint and coatings used in interior decoration also contain a lot of formaldehyde [20]. The residual formaldehyde after decoration will gradually be released into the surrounding environment [21][22][23]. Generally, the formaldehyde content of newly decorated houses will exceed the standard by more than six times, and the formaldehyde release period will last for 3–15 years [24][25][26]. In 1995, the International Agency for Research on Cancer has already identified formaldehyde as a suspected carcinogen [27][28]; in 2004, formaldehyde was upgraded from a Class II carcinogen to a Class I carcinogen [12][29]; in 2010, formaldehyde was defined as one of nine indoor air pollutants in indoor air quality guidelines issued by the World Health Organization [10][16]. Besides, as a protoplasmic toxic substance, formaldehyde can be combined with proteins as well [30][31][32]. Inhalation of high concentrations of formaldehyde may lead to respiratory edema and induce bronchial asthma [33][34][35][36]. Direct skin contact with formaldehyde can cause dermatitis, necrosis, and even skin cancer [37][38][39]. And long-term exposure to formaldehyde will cause the decline of body function and poison the nervous system, cardiovascular system, and reproductive system to some extent [38][40][41][42]. Therefore, the real-time detection of gaseous formaldehyde in an indoor environment is very important for human beings.

Sensing technology is one of the commonly used methods to monitor indoor formaldehyde [10]. Compared with the colorimetric method, chromatographic analysis, spectrophotometry, and other methods for formaldehyde monitoring, the detection of formaldehyde by gas sensors has higher sensitivity and shorter reaction time [43][44]. Briefly, these sensors based on metal oxide semiconductor (MOS) material and polymer material are the most researched gaseous formaldehyde sensors [45][46][47]. Accurate identification of formaldehyde in complex atmospheric environments is a great challenge for MOS-based sensors [48][49][50]. Compared with the MOS sensor, the development of polymer sensors started late, but the development speed is also very fast [51][52]. The advantage of polymer sensors is that they can accurately identify formaldehyde based on specific chemical reactions.

2. The Sensing Techniques for Formaldehyde Detection

Currently, resistance sensors and quartz crystal microbalance (QCM) sensors are the most common sensing types in the field of polymer and polymer nanocomposite sensors [53][54]. In addition, microelectromechanical system (MEMS) resonators, fluorescence probes, and other sensing techniques are also reported in some studies [55][56]. All of the above methods can be used to detect trace formaldehyde with high sensitivity [2]. The resistance sensor has the longest history, but its operation method is more complex [3]. The QCM sensor has the advantages of simple operation, high sensitivity, and low energy consumption [57]. At present, the QCM sensor is the most widely studied in the field of gaseous formaldehyde detection [58]. Compared with QCM sensors, MEMS sensors such as film bulk acoustic resonators have higher sensitivity due to the higher resonant frequency [59]. But now, the development of MEMS sensors is not mature enough, and the cost is high. Fluorescent sensors are used to visualize formaldehyde levels in living cells because of their good biocompatibility [60].

The resistance sensor is one of the most commonly used formaldehyde sensors with the longest history [61]. Further, the working principle of the resistance sensor is to detect the gas by recording the change in the resistance value when the sensitive material contacts the gas [62]. Good selectivity, high sensitivity, and low detection limit are the advantages of the resistance sensors [63].

In recent years, QCM has gradually replaced resistance testing and has become the most popular research direction in the field of organic polymer sensors for detecting gaseous formaldehyde [64][65]. QCM is a sensitive quality detection platform whose sensitivity is nanogram (ng) level [66]. In theory, the QCM can detect mass changes equivalent to a fraction of a monolayer or atomic layer, and the most basic principle of QCM is the piezoelectric effect of quartz crystals [67][68]. In 1959, Sauerbrey came to the conclusion that the resonant frequency change of QCM is proportional to the added mass on the quartz crystal [66][69]. On this basis, the Sauerbrey equation is summarized to represent the relationship between the mass adsorbed on the crystal sensor and the resonant frequency [29]. Based on the Sauerbrey equation, the QCM surface can be modified with different sensing materials to achieve highly sensitive detection of target gas [57]. The surface of QCM was modified with formaldehyde-sensitive materials [53]. Based on the Sauerbrey equation, the mass change on QCM is calculated according to the change frequency of QCM to realize the detection of formaldehyde gas [70]. As early as 2003, polyvinylpyrrolidone (PVP)-modified QCM has been used to determine ammonia [71]. Currently, the QCM sensor has been widely used in humidity, benzene vapor, formaldehyde vapor, and other detection fields [66][67]. Similar to QCM, MEMS are often used as mass-loading platforms when used as gas sensors. The sensitive layer is coated on the surface of the resonator to absorb the target gas molecules, and then the small mass change is monitored by the change of the resonant frequency [72]. Compared with traditional electro-acoustic resonators (such as QCM), MEMS resonators use 1–2 microns-thick piezoelectric films instead of crystal plates [73][74]. Therefore, MEMS resonators, such as thin-film volume acoustic resonators, have higher sensitivity, which has attracted wide attention in the field of gas detection [59][75].

Fluorescence is a cold luminescence phenomenon of photoluminescence [76]. In the ground state, there is no electron transition, that is, no fluorescence [35][77]. When the recognition site on the fluorescent molecule interacts with the analyte, the identified chemical signal is transmitted to the fluorophore through different signal transduction mechanisms [55]. The properties of fluorophore, such as the emission wavelength, intensity, or fluorescence lifetime of fluorescence, can be changed to realize the quantitative or qualitative detection of the measured object [78].

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