Recent Advances in Photo—Activated Chemical Sensors

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Abstract: Gas detectors have attracted considerable attention for monitoring harmful gases and air pollution because of industry development and the ongoing interest in human health. On the other hand, conventional high—temperature gas detectors are unsuitable for safely detecting harmful gases at high activation temperatures. Photo—activated gas detectors improve gas sensing performance at room temperature and enable low—power operation. This review presents a timely overview of photo—activated gas detectors that use illuminated light instead of thermal energy. Illuminated light assists in gas detection and is classified as visible or ultraviolet light. The research on photo—activated gas detectors is organized according to the type of gas that can be intensively detected. In addition, a development strategy for advancing photo—activated gas detectors is discussed.

Keywords: photo—activated gas detectors; ultraviolet; visible light; nitric oxide; nitric dioxide; formaldehyde; ammonia

1. Introduction

Gas detectors have attracted enormous attention because they can detect the emergence of a gas in areas of development for particular safety systems. To be specific, gas detectors offer rapid detection for early response to tremendous accidents with flammable [1–9], combustible gases [10–15], as well as bio—hazardous gases [16–25]. These devices are widely used in industry for continuously monitoring gas leakages [26–29] or manufacturing processes [30–33]. Gas detectors can be classified according to their operation principles: electrochemical devices [34–37], photoionization—based types [38–41], ultrasonic detectors [42–45], and semiconductor—based devices [46–49]. Among the various detector types, semiconductor—based devices allow rapid gas detection because the electrical resistance changes when it comes into contact with the target gas. Semiconductor—based gas detectors have been developed, and a variety of detectors have been reported using semiconducting materials, such as metal oxides [50–54], carbon nanotubes [55–58], two—dimensional materials, including graphene [59–62] and transition metal dichalcogenide [63–66], organic materials [67–70], and perovskites [71–74]. On the other hand, these detectors suffer cross—sensitivity with other gases; high reactivity with gases other than the target gas reduces selectivity [75–77]. Furthermore, the demand for faster recovery rates [78–80] and improved responsiveness in detecting extremely small amounts of gas [81–84] is driving the continuous development of these detectors. As an emerging approach, photo—activated or photo—assisted gas detection over diverse materials and devices has been proposed. By irradiating with light of a specific wavelength during the gas detection operation, this approach (1) enhances the photoreaction speed and recovery speed, (2) secures gas selectivity, and (3) increases the gas reactivity. The mechanism of gas sensors is different for each sensor device. Electron–hole pairs are generated by the interaction between the light irradiated on the photo—activated gas sensor and the surface of the gas—sensitive material. Photo—generated charge carriers interact with the oxygen ions of the gas—sensitive material, resulting in a change in conductivity. Figure 1 shows the surface statement of...
an n-type metal oxide semiconductor–based photo–activated gas sensor by injecting oxidizing gas and reducing gas.

![Diagram of an n-type metal oxide semiconductor-based photo-activated gas sensor](image)

**Figure 1.** Surface statement of n-type metal oxide semiconductor–based photo–activated gas sensor under oxidizing gas and reducing gas.

In this context, this review comprehensively revisits recent advances in photo–activated or photo–assisted gas detectors, emphasizing their illuminated light wavelengths and target gases. This paper reviews the recent developments in photo–activated gas detectors, classified according to the type of light source and target gas. The light sources for photo–activated gas detectors discussed in this review are ultraviolet and visible light. In addition, studies of photo–activated gas detectors with high selectivity for nitric oxide, nitric dioxide, formaldehyde, and ammonia gases are summarized. Finally, technology development strategies for photo–activated gas detectors are offered.

2. UV–Activated Gas Sensors

2.1. UV–Activated Nitric Oxide Gas Sensors

As a remarkable example of UV–activated nitric oxide gas detection, in 2020, Murali et al. presented NO gas detection using a heterojunction structure based on nitrogen–doped graphene quantum dots/titanium dioxide (TiO$_2$) named NGQDs [85]. The [001] facet form with unsaturated coordination atoms and dangling bonds led to more absorbed oxygen–related gases on the TiO$_2$ surface, inducing high responsivity on the gas sensor platform. NGQDs were fabricated by doping graphene quantum dots (GQDs) with nitrogen atoms, which increased the gas–detecting performance of the heterostructure TiO$_2$ gas sensor by increasing the charge carriers and defects. Figure 2a shows the NO gas sensing characteristics of the TiO$_2$@NGQDs sensor irradiated with UV light ($\lambda = 365$ nm). The
response to 10−100 ppm NO gas was investigated. A higher concentration of injected NO gas increased the resistance of the TiO$_2$@NGQDs sensor. The measured response time and recovery time were 235 and 285 s, respectively (Figure 2b); they were 63 s and 605 s faster than under dark conditions. When irradiated with UV light, the response speed was improved due to the more active absorption and desorption of oxygen species on the TiO$_2$ surface than under dark conditions. Furthermore, the selectivity of the TiO$_2$@NGQDs sensor was investigated (Figure 2c). The TiO$_2$@NGQDs detected 100 ppm of NO, H$_2$S, H$_2$, and CO at room temperature. On the other hand, the response to NO gas was up to seven times higher than other gases. When n−type TiO$_2$ and p−type NGQDs have heterostructures, the excess electrons of TiO$_2$ move to NGQDs due to the relatively low bandgap of TiO$_2$. The NO gas injected into the TiO$_2$@NGQDs sensor interacts with surface oxygen ions and electrons in TiO$_2$, which reduces the carrier concentration of TiO$_2$. On the other hand, when the TiO$_2$@NGQDs sensor is irradiated with UV light, it interacts with the generated photoelectrons and oxygen on the surface to produce oxygen ions. The additionally generated UV light–induced oxygen ion species interact with the larger number of electrons in TiO$_2$.

As another example, a p−n heterostructure was used to detect NO gas. He et al. represented a UV−activated NO gas sensor operable at room temperature using Cu−TCA (H$_3$TCA = tricarboxytriphenylamine) and TiO$_2$ nanochannels (TiNCs) as a p−n heterostructure [86]. The Cu−TCA porous structure, due to the metal−organic framework (MOF), allows only the NO gas contained in the mixed gas to be adsorbed, providing selectivity for NO gas. In addition, the porous structure has many active sites for absorbing more NO molecules. The TiNCs as photocatalytic materials showed improved NO gas sensing characteristics owing to their high surface−to−volume ratio and stable chemical character-

Figure 2. (a) Response of the TiO$_2$@NGQDs sensor under UV irradiated; (b) response and recovery times of TiO$_2$@NGQD sensors with UV−on and UV−off; (c) selectivity characteristics of the TiO$_2$@NGQDs sensor (adapted from [85] with permission from the American Chemical Society); (d) image of the flexible and wearable TiO$_2$@NGQDs sensor with human arm and wrist; (e) response of the Cu−TCA/TiNCs sensor ppb with UV−on and UV−off; (f) response and recovery time of the Cu−TCA/TiNCs sensor (adapted from [86] with permission from the American Chemical Society).
istics. Figure 2d presents an image of a flexible Cu–TCA/TiNCs sensor attached to human skin. Polydimethylsiloxane (PDMS) was used as a substrate for the Cu–TCA/TiNCs sensor, and the S–shaped Cu electrode prevented damage due to fatigue deformation. The performance of the Cu–TCA/TiNCs sensor was improved when irradiated with UV light (λ = 365 nm). Figure 2e shows the NO gas response of the Cu–TCA/TiNCs sensor in dark and UV light–irradiated conditions with a range of 5–200 ppm NO gas injected. The NO gas response of the Cu–TCA/TiNCs sensor with UV light irradiation was increased from 1.5–fold to 3.4–fold compared with the dark condition. The UV irradiation effect reduced the response time of the Cu–TCA/TiNCs sensor owing to the large carrier concentration and active sites. Furthermore, the recovery time decreased owing to the accelerated activation of the surface to return to its initial state. Figure 2f shows the response speed of the Cu–TCA/TiNCs sensor. The response and recovery time were decreased by 101.2 s and 106 s compared to the dark conditions. The Cu–TCA/TiNCs sensor detected NO molecules due to a change in resistance by reactive oxygen species. The NO molecules capture electrons in the Cu–TCA/TiNC conduction band and interact with oxygen ions on the surface to form NO and N2 ions. As a result, the NO and N2 ions adsorbed on the surface increase the resistance of Cu–TCA/TiNC. On the other hand, UV light increases the response of the Cu–TCA/TiNCs sensor to NO gas. The electron–hole pairs generated by UV light produce many oxygen ions that interact more with the NO molecules in the dark. As a result, the width of the depletion layer was larger than in the dark, resulting in high resistance.

2.2. UV–Activated Nitric Dioxide Gas Sensors

As a representative UV–activated nitric dioxide gas detection study, in 2019, Wang et al. reported a nitric dioxide (NO2) gas sensor with improved sensing performance by treating ZnO nanowires (NW) with NaBH4 [87]. The oxygen vacancies (V_O) on the surface of the ZnO nanowires treated hydrothermally with NaBH4 increase the chemisorption of oxygen species and NO2 molecules. In addition, the UV irradiation effect generates many oxygen ions and promotes the formation of NO3−, which effectively improves the detection performance of NO2 gas. Figure 3a,b show the changes in resistance of the ZnO nanowire sensor and the Vo–ZnO NW sensor with the NaBH4 treatment. Under UV (λ = 325 nm) irradiation and dark conditions, the NO2 gas sensors detected 1 ppm NO2 gas. The variation in resistance of the NO2 gas sensors depending on the initial air condition was 0.20 MΩ. Subsequently, when NO2 gas was injected into the NO2 gas sensors in the dark, the resistance of the Vo–ZnO NW was increased by approximately 2.25 MΩ compared to the ZnO NW. In other words, Vo–ZnO NW adsorbs many NO2 molecules due to the increased surface defects, resulting in higher changes in resistance. Under UV irradiation, the NO2 gas sensors showed resistance changes of 0.1 MΩ in air and 0.17 MΩ in NO2, respectively. UV irradiation enhanced the response and recovery time of the Vo–ZnO NW sensor. The response and recovery times of the Vo–ZnO NW sensor in UV irradiation conditions were 31 s and 144 s, respectively. The response and recovery times were reduced by 30 s compared to the dark conditions. Figure 3c shows the various gas sensing performances of the Vo–ZnO NW sensor under UV irradiation conditions. The response of NO2 gas was 700%, which has high gas sensing selectivity characteristics compared to other gases. In air, photoelectrons generated by UV irradiation on the Vo–ZnO NW sensor combined with oxygen species and were trapped in V_O to produce oxygen species. Subsequently, NO2 gas was injected, and the increased oxygen species interacted with the NO2− species to promote NO3− production. As a result, the depletion width was thicker, inducing high resistance.
species interacted with the NO$_2^-$ species to promote NO$_3^-$ production. As a result, the depletion width was thicker, inducing high resistance.

To fabricate the gas sensor, transition metal dichalcogenides (TMDs) were used, which have excellent electrical and optical characteristics. Kumar et al. demonstrated a MoS$_2$-based NO$_2$ gas detection at ambient temperature using UV light illumination [88]. MoS$_2$ was grown through the CVD process, and the annealing process was performed. Figure 3d presents a schematic diagram of the MoS$_2$-based gas sensor operating under UV irradiation ($\lambda = 365$ nm). The MoS$_2$-based gas sensor was fabricated by growing MoS$_2$ on SiO$_2$/Si substrates by CVD. The Au/Cr (200 nm/5 nm) electrodes were deposited by thermal evaporation, and the widths of the electrodes were 100 and 250 $\mu$m, respectively.

The response time of the MoS$_2$-based gas sensor to NO$_2$ gas under UV light irradiation conditions was investigated (Figure 3e). The MoS$_2$-based gas sensor was injected with 100 ppm NO$_2$ gas. The response time was defined as the time until the saturation of the relative response reached 90% after the NO$_2$ gas was injected. The response time of the MoS$_2$-based gas sensor in UV conditions was 29 s, which was approximately 42 s faster than the gas response by thermal activation (100 °C). Figure 3f shows the relative responses of the MoS$_2$-based gas sensor to various gases. The relative response of the NO$_2$ gas measured was approximately 21%, which has the highest selectivity compared to other gases.
the relative response reached 90% after the NO\textsubscript{2} gas was injected. The response time of the MoS\textsubscript{2}−based gas sensor in UV conditions was 29 s, which was approximately 42 s faster than the gas response by thermal activation (100 °C). Figure 3f shows the relative responses of the MoS\textsubscript{2}−based gas sensor to various gases. The relative response of the NO\textsubscript{2} gas measured was approximately 21%, which has the highest selectivity compared to other gases.

A gas sensor with a high surface−to−volume ratio was achieved using one−dimensional carbon nanotubes (CNT). Drozdowska et al. used a carbon nanotube network (CNN) to fabricate NO\textsubscript{2} gas sensors with a high surface−to−volume ratio [89]. The CNTs have p−type semiconductor characteristics and high sensitivity to gases owing to the large number of bonding sites on their large surface. The CNN is sensitive to UV light irradiation and improves response speed. The UV light used in this study has a wavelength of 365 nm and 275 nm, respectively, and can detect at least 1 ppm of NO\textsubscript{2}. Figure 3g shows the response of the CNN gas sensor to 20 ppm NO\textsubscript{2} gas. The NO\textsubscript{2} gas response increases with the amount of UV light irradiated to the CNN gas sensor. Furthermore, the initial resistance of the CNN gas sensor increases as the UV−on and UV−off cycles are repeated. The response of the CNN sensor to various NO\textsubscript{2} gases was investigated. Figure 3h shows the NO\textsubscript{2} gas response of the CNN sensor in the dark. NO\textsubscript{2} gas concentrations below 4 ppm are difficult to detect in the dark. On the other hand, the CNN gas sensor irradiated with UV light improves the sensing performance to detect low concentrations of NO\textsubscript{2} gas, such as 1 ppm (Figure 3i). As a result, the UV irradiation increases the NO\textsubscript{2} gas response of the CNN sensor. The resistance of the CNN gas sensor increased when NO\textsubscript{2} was injected, and UV light irradiation increased the resistance change. UV−generated holes interact with negatively charged ions on the CNT surface, resulting in oxygen desorption. At this point, the lowered hole concentration reduces the conductivity of the CNN sensor. Additionally, the UV wavelength means that more energy is applied to the CNN sensor, resulting in the effective desorption of gas molecules, and accordingly, a rapid recovery of the CNN sensors was achieved.

### 2.3. UV−Activated Formaldehyde Gas Sensors

For enhancing the responsiveness of the gas sensor, a porous structure was used. Li et al. reported the formaldehyde (HCHO) gas sensor by loading Au on the porous octahedrons’ (POHs) structured ZnO surface [90]. ZnO is an n−type metal oxide that has the advantages of being low−cost and nontoxic and is used as the core material of gas sensors. On the other hand, to improve the performance of ZnO−based gas sensors, operation at high temperatures leads to high power consumption. As a solution, UV light irradiation makes ZnO−based gas detectors operate at ambient temperature, but it has a low response. The porous structure was introduced into the MOS to improve the responsivity of the gas sensor due to the high surface−to−volume ratio. Furthermore, chemical catalytic materials, such as Au, are loaded into ZnO to produce a Schottky junction, leading to improved gas sensing performance. Figure 4a shows the HCHO gas response of a ZnO POH sensor and an Au−loaded ZnO POH sensor (Au−ZnO POH). The UV light used had a wavelength of 365 nm, and 50–800 ppm HCHO gas was investigated. The Au−ZnO POH sensor has more responsiveness for all concentrations of HCHO gas than the ZnO POH sensor. In particular, the responsiveness of 800 ppm HCHO gas doubled. In this way, the Au loading effect improves its response toward HCHO molecules. In addition, the selectivity of the Au−ZnO POH sensor was investigated. Figure 4b shows the responsiveness of the Au−ZnO POH sensor to various gases. Methanol, ethanol, acetone, benzene, and formaldehyde with a concentration of 400 ppm were assessed. The responses of the Au−ZnO POH sensor to all these gases were superior to those of the ZnO POH sensor. Figure 4c shows the resistance changes in the ZnO POH and Au−ZnO POH sensors exposed to the HCHO gas. The Au loading allows more oxygen molecules to be adsorbed onto the ZnO POH surface, leading to a thicker depletion layer resulting in high resistance.
In 2021, Chang et al. produced a HCHO gas sensor based on the heterostructure of TiO$_2$ and SnO$_2$ to detect low HCHO gas concentrations [91]. The synergy between SnO$_2$ in a porous structure and TiO$_2$ as a photocatalytic material resulted in a high surface area that detected HCHO gas selectively, leading to an improved response of the gas sensor. Figure 4d shows the fabrication process of the SnO$_2$@TiO$_2$ gas sensor. Ti (10 nm) and Pt (150 nm) electrodes were deposited in an interdigitated shape on a SiO$_2$/Si substrate. Subsequently, SnO$_2$ and TiO$_2$ were deposited sequentially. SnO$_2$ has a nanoporous structure due to the kinetic energy of argon gas injected during the thermal evaporation process. Such a nanoporous structure can increase the response of the SnO$_2$@TiO$_2$ gas sensor because of its high surface to volume ratio and large surface area for activation. TiO$_2$ with photocatalytic material was deposited using atomic layer deposition (ALD). Figure 4e shows the HCHO gas response characteristics of the SnO$_2$@TiO$_2$ sensor in UV–on and UV–off. The wavelength of the irradiated UV light was 365 nm, and the concentration of the injected HCHO gas was 0.1–10 ppm. The response of the SnO$_2$@TiO$_2$ sensor irradiated with UV–on was increased compared to the UV–off. The increased resistance change caused by UV light irradiation allows the sensor to detect lower HCHO gas concentrations.
In particular, the change in resistance to 0.1 ppm HCHO gas with UV—on increased by approximately 16% compared to UV—off. Figure 4f shows the selectivity of the SnO2@TiO2 sensor. Compared to ammonia, carbon monoxide, and acetone gas, the response to HCHO gas at 3 ppm was 40%. The electron–hole pairs generated by the UV produced reactive oxygen species on the TiO2 surface. The injected HCHO molecules interacted with the adsorbed oxygen ions on the TiO2 surface and released electrons. As a result, the released electrons accumulated in the TiO2 conduction band and reduced the resistance.

To improve the responsiveness of a ZnO—based HCHO gas sensor, Yang et al. decorated nickel sulfide (NiS) nanomaterials onto Ni—doped ZnO [92]. The Ni—ZnO restrained the recombination of photo—generated electrons by UV light irradiation and increased carrier concentration. In addition, the NiS nanomaterials improved the response time of the NiS/Ni—ZnO gas sensors. Figure 4g shows the response of the HCHO gas range from 2 to 10 ppm with UV light irradiation (λ = 365 nm). The pure ZnO, Ni—ZnO, and NiS/Ni—ZnO gas sensors were compared to investigate the response of the HCHO gas. NiS decorating enhanced the response of the gas sensor. The response of the 0.4% Ni—ZnO gas sensor to 10 ppm of HCHO gas was 275%. On the other hand, the response of the 0.2% NiS/0.4% Ni—ZnO gas sensor was improved by 330%. Furthermore, the NiS improved the response time of the NiS/Ni—ZnO gas sensor. As shown in Figure 4h, the response time of the NiS/Ni—ZnO gas sensor was 37.8 s, which was significantly faster than the Ni—ZnO gas sensor with a response time of 131.5 s. Temporal photovoltage (TPV) characterizations were performed to investigate the transfer properties of photoexcited charge carriers (Figure 4i). The increased TPV response showed that the NiS/Ni—ZnO gas sensor has more photo—generated charges. In addition, the NiS/Ni—ZnO gas sensors have the fastest time to reach maximum TPV. In other words, the NiS decorated on Ni—ZnO improves the HCHO gas response time of the NiS/Ni—ZnO gas sensor by enhancing the separation and transmission efficiency of the photo—excited electrons and holes. UV light irradiation increased the change in resistance of the NiS/Ni—ZnO gas sensor. Oxygen in the air adsorbed to the surface of ZnO—based materials interacts with electrons in the ZnO conduction band promoted by UV light to generate oxygen ions. At this time, the Ni doping effect provided sites for trapping holes, enlarged oxygen ions adsorbed on the surface compared to pure ZnO. Oxygen ions adsorbed on the surface make the depletion layer of the NiS/Ni—ZnO gas sensor thicker. When HCHO gas was injected, the oxygen ions interacted with the HCHO molecule and generated electrons. The generated electrons were then transferred to the conduction band of the ZnO, increasing its conductivity.

2.4. UV—Activated Ammonia Oxide Gas Sensors

MOS and organic semiconductors were used to fabricate the ammonia (NH3) gas sensor. Safe et al. produced an NH3 gas sensor using a heterojunction of a p—type semiconductor polyaniline (PANI) and n—type semiconductor one—dimensional TiO2 nanofibers [93]. PANI, with a porous morphology, detected NH3 molecules selectively at room temperature, and TiO2 has a photocatalytic function. The PANI/TiO2 core—shell sensor, in which the two semiconductor materials were applied simultaneously, exhibited improved photocatalytic properties and selective NH3 gas response in a UV light irradiation. The PANI/TiO2 core—shell sensor was irradiated with UV at a wavelength of 365 nm to investigate the change in resistance. Figure 5a shows the resistance change in the sensor with a TiO2 core created from a material containing a 30% anatase— 70% rutile mixed crystal phase. The sensor shows improved photocatalytic characteristics compared to the sole rutile crystal phase. The PANI/TiO2 core—shell sensor was exposed to 50 ppb to 40 ppm NH3 gas, and the electrical response was measured. The PANI/TiO2 core—shell sensor had a response time of 63 s and a recovery time of 37 s when 1 ppm of NH3 gas was injected. Figure 5b shows the stability of the PANI/TiO2 core—shell sensor measured at 15—day intervals. The response of 1 ppm NH3 gas was measured under UV light irradiation. The gas sensor in which the core of TiO2 has an anatase—rutile phase showed an approximately 22% decreased response when exposed to UV light because of the
reduced activity of the photocatalyst. In addition, the selective gas response performance for NH₃ gas increased when the PANI/TiO₂ core–shell sensor was irradiated with UV light (Figure 5c). UV irradiation improved the response time and recovery time of the PANI/TiO₂ core–shell sensor.

In 2018, Zhou et al. first reported a UV–enhanced NH₃ detection sensor using graphene oxide nanosheets (rGO), TiO₂ NPs, and Au NPs [94]. The rGO acted as the template to attach the TiO₂ NPs and Au NPs and produced a high electron collector and transporter. The rGO with high conductivity detected changes in resistance effectively without heating. TiO₂ NPs are photocatalytic materials that interact with UV light and NH₃ molecules. Au NPs increase the sorption sites on the surface to detect sorption molecules and promote charge separation of electron–hole pairs generated by UV light. Figure 5d shows a schematic diagram of the rGO/TiO₂/Au sensor. To fabricate the rGO/TiO₂/Au sensor, Si/SiO₂ was used for the substrate. Subsequently, Au (120 nm)/Ti (40 nm) electrodes

![Figure 5. (a) Resistance change in the PANI/TiO₂ core–shell sensor; (b) stability of the PANI/TiO₂ core–shell sensor with UV irradiation; (c) selectivity characteristics of the PANI/TiO₂ core–shell sensor (adapted from [93] with permission from the Elsevier B.V.); (d) schematic diagram of the rGO/TiO₂/Au sensor; (e) response of the rGO/TiO₂/Au sensor with UV–on and UV–off; (f) gas selectivity characteristics of the PANI/TiO₂ core–shell sensor; (g) selectivity of the pure 2DPI, pure In₂O₃, and the 2DPI/In₂O₃ gas sensor under various gases; (h) response of the pure 2DPI, pure In₂O₃, and the 2DPI/In₂O₃ gas sensor with UV light irradiation; (i) long–term stability of the 2DPI/In₂O₃ gas sensor (adapted from [95] with permission from the Elsevier B.V.).](image-url)
were formed into planar interdigital shapes, and a conventional photolithography and lift-off process was used for patterning. In addition, the width of the electrode was 50 μm. The synthesized rGO/TiO₂/Au solution was spray-coated on the prepared substrate and thermally treated in a vacuum oven. Figure 5e shows the NH₃ gas response characteristics of the rGO/TiO₂/Au sensor under UV irradiation (λ = 365 nm) and dark conditions. The response to NH₃ gas is higher under UV irradiation than in the dark. The NH₃ gas response of the rGO/TiO₂/Au sensor with UV irradiation increased to 2.1% compared to the dark conditions. Additionally, response speed and recovery level were enhanced by 234 s and 43%, respectively. In addition, the selective characteristics of the rGO/TiO₂/Au sensor were investigated. Figure 5f shows the gas response to NH₃ (Figure 6a). First, finger-shaped Au electrodes were deposited on the substrate. Diethylammonium chloride (DEAC) was added to 2DPI/In₂O₃ film solution to achieve the film deposition. The film solution was sprayed on the prepared substrate and thermally treated in a vacuum oven at 150 °C for 1 h. To complete the gas sensor assembly, 2DPI/In₂O₃ and rGO/TiO₂/Au sensors were fabricated. Figure 5g shows the long-term stability of the 2DPI/In₂O₃ gas sensor for ammonia gas detection. Over 150 days, 0.1, 0.5, 1, and 5 ppm of NH₃ gas could be detected without degradation. The heterojunction of the 2DPI/In₂O₃ gas sensor improved the electrical conductivity. In Fermi level equilibrium, the electrons of 2DPI move into In₂O₃, making the depletion layer smaller.

3. Visible—Activated Gas Sensors

3.1. Visible—Activated Nitric Oxide Gas Sensors

In 2019, Chinh et al. reported a ZnO–based NO gas sensor loaded with an Au NP catalyst [96]. The energy of visible light irradiated to Au NPs reduced the barrier energy of ZnO, activating the adsorption and desorption of NO and oxygen molecules. A 2.5 mm × 2.5 mm Al₂O₃ substrate was prepared to fabricate the Au/ZnO gas sensor (Figure 6a). First, finger-shaped Au electrodes were deposited on the substrate. Diethyl...
zinc \([\text{Zn(C}_2\text{H}_5)_2]\) and \(\text{H}_2\text{O}\) were then flowed alternately through ALD to deposit a \(\text{ZnO}\) thin film. Subsequently, an annealing treatment was performed at 500 \(\degree\text{C}\) for two hours. The \(\text{Au NPs}\) were loaded on the \(\text{ZnO}\) thin film by immersing the films in an \(\text{Au colloidal solution}\) and annealing them at 500 \(\degree\text{C}\). The wavelengths of the light—emitting diode (LED) used to measure the \(\text{Au/ZnO gas sensor}\) were ultraviolet \((\lambda = 382 \text{ nm})\), blue \((\lambda = 439 \text{ nm})\), and green \((\lambda = 525 \text{ nm})\), and light with an intensity of 0.76 mW/cm\(^2\) was irradiated. Figure 6b shows the response of the \(\text{Au/ZnO gas sensor}\) to various wavelengths of light when exposed to 10 ppm NO gas. The \(\text{Au/ZnO gas sensor}\) exhibited the strongest response of more than 12 in blue light irradiation. In addition, the resistance of the \(\text{Au/ZnO gas sensor}\) was increased because the Schottky contact was bent more. Figure 6c shows the selectivity of the \(\text{Au/ZnO gas sensor}\). The response of 150 ppm of \(\text{NH}_3\), \(\text{H}_2\text{S}\), \(\text{H}_2\), \(\text{CO}\), and \(\text{CH}_4\) gases was investigated. On the other hand, the responses to other gases were lower than that of 10 ppm NO gas.

3.2. Visible−Activated Nitric Dioxide Gas Sensors

In\(_2\text{O}_3\) nanowires (NWs) synthesized by electrospinning improve the responsivity of gas sensors with a high surface area. Zhang et al. produced a NO\(_2\) gas sensor based on In\(_2\text{O}_3\) nanowires (NWs) [99]. In\(_2\text{O}_3\) is an n−type MOS with a bandgap of 2.8 eV and high conductivity that exhibits responsivity and selectivity to NO\(_2\) gas. The In\(_2\text{O}_3\) NWs have a high surface area and a loose arrangement, which promotes the interaction between the NO\(_2\) molecules and oxygen species. Defects in the In\(_2\text{O}_3\) NWs and oxygen species absorbed on the surface increase the responsivity to NO\(_2\) gas. On the other hand, the In\(_2\text{O}_3\) NWs gas sensor has a long recovery time in the dark. To achieve a rapid recovery time, irradiating visible light promotes the removal of adsorbed NO\(_2\) gas from the In\(_2\text{O}_3\) NWs gas sensor. Figure 7a shows the response of the In\(_2\text{O}_3\) NWs gas sensor when exposed to 5 ppm NO gas.
To fabricate NO gas sensors with improved reactivity under visible light irradiation, Xie et al. used tin oxide (SnO$_2$) and graphene quantum dots (GQDs) [97]. SnO$_2$, an n-type MOS, has a bandgap of 3.60 eV and is used as a core material in gas sensors because of its excellent electrical and optical characteristics. Nevertheless, it is difficult to use visible light for a SnO$_2$-based sensor with a wide bandgap. Hence, SnO$_2$ and GQDs with a narrow bandgap material were combined to fabricate high-response gas sensors. The GQDs improved the charge separation efficiency when irradiated with visible light. The photocatalytic characteristics were investigated according to the GQD content. Figure 6d shows the photocatalytic spectrum for the NO gas under visible light irradiation. All samples were exposed to 600 ppb of NO gas, and the adsorption-desorption state was equilibrated by exposure to the NO gas for 30 minutes before visible light irradiation. The NO removal rate with only SnO$_2$ was 18%, whereas it increased dramatically when GQDs were deposited on SnO$_2$. The rate of NO gas removal reached 57% when the amount of GQDs was 1%. On the other hand, excessive deposition of GQDs reduces light efficiency because it blocks the active site of SnO$_2$. Figure 6e shows a cycle test for the NO gas under visible light irradiation. During the five cycles, the degradation product accumulated and deteriorated the photoactivity. Figure 6f shows the photocurrent densities of the pure SnO$_2$ and SnO$_2$/GQDs under visible light irradiation. The improved charge separation efficiency due to QGD increased the response of the SnO$_2$/GQDs sensor under visible light illumination.

In 2021, Geng et al. reported a heterojunction-structured NO gas sensor using carbon nitride (g-$\text{C}_3\text{N}_4$) and hematite (α-$\text{Fe}_2\text{O}_3$) [98]. g-$\text{C}_3\text{N}_4$ is a photocatalytic material but shows poor performance for NO removal gas due to rapid electron–hole recombination and low light harvesting ability. The photocatalytic efficiency was increased by combining α-$\text{Fe}_2\text{O}_3$ with g-$\text{C}_3\text{N}_4$ to achieve a heterojunction structure of the Z-scheme. The presented 2D/2D structure has a high interfacial area and active sites for interacting with NO molecules and effectively absorbing visible light to promote charge separation and transport. Figure 6g shows the photocatalytic performance of the α-$\text{Fe}_2\text{O}_3$/g-$\text{C}_3\text{N}_4$ sensors with different composite ratios of NO removal. The α-$\text{Fe}_2\text{O}_3$/g-$\text{C}_3\text{N}_4$ sensor was irradiated with visible light using a Xe lamp with a 400 nm cutoff filter applied. The NO gas removal performance of pure α-$\text{Fe}_2\text{O}_3$ and g-$\text{C}_3\text{N}_4$ was 3.4% and 34.2%, respectively. On the other hand, the NO gas degradation efficiency increased when the heterojunction was formed. Overall, the charge separation efficiency increased with increasing α-$\text{Fe}_2\text{O}_3$ content. The highest NO gas degradation efficiency of 60.8% was observed when the α-$\text{Fe}_2\text{O}_3$ content was 7%. Figure 6h shows the NO gas removal rate of 7% α-$\text{Fe}_2\text{O}_3$/g-$\text{C}_3\text{N}_4$ over five cycles. The optimized α-$\text{Fe}_2\text{O}_3$ content barely changed the NO removal efficiency and stabilized the sensor. Figure 6i shows the photocurrent response of various samples. Similarly, pure α-$\text{Fe}_2\text{O}_3$ and g-$\text{C}_3\text{N}_4$ had the lowest photocurrent density. However, 7% α-$\text{Fe}_2\text{O}_3$/g-$\text{C}_3\text{N}_4$ had the highest photocurrent density. An appropriate α-$\text{Fe}_2\text{O}_3$ content produces a g-$\text{C}_3\text{N}_4$ active area with enhanced NO gas degradation efficiency and photocurrent density.

3.2. Visible-Activated Nitric Dioxide Gas Sensors

In$_2$O$_3$ nanowires (NWs) synthesized by electrospinning improve the responsivity of gas sensors with a high surface area. Zhang et al. produced a NO$_2$ gas sensor based on In$_2$O$_3$ nanowires (NWs) [99]. In$_2$O$_3$ is an n-type MOS with a bandgap of 2.8 eV and high conductivity that exhibits responsivity and selectivity to NO$_2$ gas. The In$_2$O$_3$ NWs have a high surface area and a loose arrangement, which promotes the interaction between the NO$_2$ molecules and oxygen species. Defects in the In$_2$O$_3$ NWs and oxygen species absorbed on the surface increase the responsivity to NO$_2$ gas. On the other hand, the In$_2$O$_3$ NWs gas sensor has a long recovery time in the dark. To achieve a rapid recovery time, irradiating visible light promotes the removal of adsorbed NO$_2$ gas from the In$_2$O$_3$ NWs gas sensor. Figure 7a shows the response of the In$_2$O$_3$ NWs gas sensor when exposed to 5 ppm of NO$_2$ gas. Visible light has a wavelength range of 400 to 700 nm and was irradiated with...
an intensity of 4.58 mW/cm². The resistance was restored to 90% of the initial value in approximately 20 s when the In₂O₃ NWs gas sensor was irradiated by visible light, and at the same time, the NO₂ gas flow was stopped. In addition, repeated tests were performed to confirm the stability of the In₂O₃ NWs gas sensor (Figure 7b). The In₂O₃ NWs gas sensor was controlled in visible light, and the changed resistance reached the initial value during five cycles without deterioration. Figure 7c shows the selectivity characteristics of the In₂O₃ NWs gas sensor. The response to 5 ppm NO₂ gas was highest at 740. On the other hand, the responses to ethanol, formaldehyde, and toluene gas were negligible. In addition, NO, NH₃, and H₂S gases showed stronger responses than volatile organic compounds (VOCs) but were significantly lower than NO₂ gas. The initial resistance of the In₂O₃ NWs gas sensor is determined by the oxygen species adsorbed on the surface. When the In₂O₃ NWs gas detectors were exposed to NO₂ gas, oxygen—related gases on the surface and electrons extracted from the conduction band of In₂O₃ NWs interacted and increased the resistance. On the other hand, photons generated by visible light irradiation desorb the oxygen ions from the surface. Thus, the released electrons were transported to In₂O₃ nanowires, reducing the resistance.

**Figure 7.** (a) Response of the In₂O₃ NWs gas sensor with visible light irradiation; (b) stability characteristics of the In₂O₃ NWs gas sensor; (c) selectivity characteristics of the In₂O₃ NWs gas sensor (adapted from [99] with permission from the Elsevier B.V.); (d) response of the Au–MoS₂ gas sensor with UV and visible light; (e) response of the Au–MoS₂ gas sensor with various NO₂ gas concentration; (f) selectivity characteristics of the Au–MoS₂ gas sensor (adapted from [100] with permission from the American Chemical Society); (g) electrical resistance response of the rGO@ZnO sensor with white light illumination; (h) repeated NO₂ gas response of the rGO@ZnO sensor; (i) selectivity characteristics of the rGO@ZnO sensor (adapted from [101] with permission from the Elsevier B.V.).
To enhance the detection limit of a MoS$_2$–based NO$_2$ gas sensor, Chen et al. loaded Au NPs on MoS$_2$ to use the localized surface plasmon resonance (LSPR) effect [100]. The decorated Au NPs irradiated with optimized light, the strong absorption of light, and the enhanced electromagnetic near-field due to the LSPR effect increase the light absorption efficiency of MoS$_2$. In addition, Au$-$MoS$_2$, with its high surface$-$to$-$volume ratio structure, provides more opportunity to interact with NO$_2$ gas. Figure 7d shows the response of the Au$-$MoS$_2$ gas sensor to the NO$_2$ gas with various wavelengths of light ($\lambda = 365, 420, 495, 530,$ and $660$ nm) irradiated. The power of the visible light source irradiated to the Au$-$MoS$_2$ gas sensor was the same as $10$ W, and $5$ ppm NO$_2$ gas was injected. Visible light at $530$ nm was optimized for NO$_2$ gas detection. The frequency of visible light at $530$ nm and the vibration frequency of Au NPs correspond. Au NPs absorb more photon energy because of the matched frequency. As a result, the Au$-$MoS$_2$ gas sensor has an LSPR effect with strong absorption for $530$ nm visible light. In addition, the response to different concentrations of NO$_2$ gas was investigated (Figure 7e). The Au$-$MoS$_2$ gas sensor detected $10$ ppb to $50$ ppm NO$_2$ gas, and the irradiated light improved the detection limit of NO$_2$ gas. Figure 7f shows the selectivity of the pure MoS$_2$ and Au$-$MoS$_2$ gas sensors in the dark and under visible light illumination. The pure MoS$_2$–based gas sensor showed the weakest response to all gases. On the other hand, the response to NO$_2$ gas increased when loaded with Au NPs. In addition, irradiation with $530$ nm visible light further enhanced the gas response to NO$_2$ gas.

In 2021, Geng et al. synthesized reduced graphene (rGO) and used oxygen–deficient zinc oxide (ZnO$_{1-x}$) composites using hydrothermal methods. Based on these combinations, they produced an NO$_2$ gas detector operating at ambient temperature [101]. Donor defects generated during synthesis narrow the bandgap of ZnO, allowing it to respond to visible light. In addition, the rGO effectively absorbs light with its large surface area and electron mobility. The p$-$n junction produced at the ZnO interface attached to the rGO enhanced the NO$_2$ sensing response to white light. Figure 7g shows the electrical resistance response of the rGO@ZnO sensor to $50$ to $400$ ppb of NO$_2$ gas. The rGO@ZnO sensor was irradiated with white light with an intensity of $0.15$ W/cm$^2$. The rGO@ZnO sensor showed improved responsivity compared to the pure ZnO sensor. The pure ZnO sensor had a response of $0.19$ at $50$ ppm NO$_2$ gas, while the rGO@ZnO sensor showed a response of $2.31$. The increased response to low$-$concentration NO$_2$ gas improved the detection limit of the rGO@ZnO sensor. Figure 7h shows the response to the $100$ ppb NO$_2$ gas repeated test. The rGO@ZnO sensor under white light irradiation showed repeated sensing without significant degradation. In addition, the selectivity characteristics of the rGO@ZnO sensor were investigated (Figure 7i). The concentrations of SO$_2$, CO, and NH gases injected into the rGO@ZnO sensor were $100$ ppm. In addition, $400$ ppm H$_2$ gas and $10$ ppm HCHO gas were injected. Finally, the concentration of NO$_2$ gas was $100$ ppb, which was the lowest concentration but led to the strongest response.

### 3.3. Visible$-$Activated Formaldehyde Gas Sensors

In 2021, Song et al. produced an HCHO gas detector using P$-$type material, HoFeO$_3$ NPs, with high responsivity in light at various wavelengths ($\lambda = 365, 470, 530,$ and $660$ nm) [102]. In particular, the HoFeO$_3$ gas sensor showed the most enhanced response to red light ($\lambda = 660$ nm). Figure 8a shows the HCHO gas response of the HoFeO$_3$ gas sensor in the dark under and various light illuminations. The HoFeO$_3$ gas detectors were exposed to $100$ ppb to $100$ ppm HCHO gas. The lowest detection limit of the HoFeO$_3$ gas sensor was $0.5$ ppm, and the response was $0.64$. On the other hand, the response to HCHO gas was improved when the HoFeO$_3$ gas sensor was irradiated with red light. Figure 8b shows the response of the HoFeO$_3$ gas sensor to red light irradiation. Compared to the dark condition, the response to HCHO gas improved under red light irradiation, and the response was $1.9$ when exposed to $80$ ppb HCHO gas. The selectivity of the HoFeO$_3$ gas sensor was investigated (Figure 8c). The HCHO, C$_2$H$_5$O, CH$_3$COCH$_3$, NH$_3$, and CH$_3$OH gases with concentrations of $100$ ppm were injected into the HoFeO$_3$ gas sensor. In particular, the
HCHO gas showed a high response when irradiated with 660 nm and 365 nm light. In addition, the HoFeO$_3$ gas sensor had a strong response to NH$_3$. The HoFeO$_3$ gas sensor showed decreased resistance with NH$_3$ gas but increased resistance when exposed to HCHO gas. Thus, the two gases could be distinguished owing to their opposite tendency to change the resistance.

Figure 8. (a) Response of the HoFeO$_3$ gas sensor under dark and various visible light; (b) response of the HoFeO$_3$ gas sensor under red light irradiation; (c) selectivity characteristics of the HoFeO$_3$ gas sensor (adapted from [102] with permission from the Elsevier B.V.); (d) response of the MoS$_2$/rGO hybrid gas sensor in the dark condition and visible light irradiation; (e) responses of pure MoS$_2$, rGO, and MoS$_2$/rGO hybrid gas sensors; (f) response of the MoS$_2$/rGO hybrid gas sensor to 1–50 ppm HCHO gas (adapted from [103] with permission from the Elsevier B.V.).

The synergy of TMDs and graphene improved HCHO detection performance under visible light irradiation. In 2020, Wang et al. reported a MoS$_2$/rGO–based HCHO gas sensor [103]. MoS$_2$ acts as a photocatalyst material and oxidizes HCHO gas to CO$_2$ and H$_2$O when irradiated with visible light. In addition, rGO induces efficient charge separation. Figure 8d shows the response of the MoS$_2$/rGO hybrid gas sensor irradiated with visible light ($\lambda > 420$ nm) to 10 ppm HCHO gas. In addition, the responsivity under dark conditions was measured to compare to visible light irradiation conditions. When irradiated with visible light, the response time of the MoS$_2$/rGO hybrid gas sensor was 17 s, which is approximately 62 s less than in the dark condition. In addition, the resistance to HCHO gas increased. The initial resistance of the MoS$_2$/rGO hybrid gas sensor under visible light irradiation was 149 k$\Omega$, which increased by 262 k$\Omega$ upon exposure to HCHO gas, resulting in an improved response of 64%. On the other hand, the response to HCHO gas was improved by 8.5% under dark conditions. The sensing responses of pure MoS$_2$, rGO, and MoS$_2$/rGO hybrid gas sensors were compared (Figure 8e). The response under dark and visible light conditions was compared with 10 ppm of injected HCHO gas. Although pure MoS$_2$ and rGO gas sensors have less than approximately 12% response, the MoS$_2$/rGO hybrid gas sensor with both materials applied has more than 60% response in visible light.
Figure 8f shows the response of the MoS\(_2\)/rGO hybrid gas sensor to exposure to 1 to 50 ppm HCHO gas. The MoS\(_2\)/rGO hybrid gas sensor exhibited a 12.6\% response to 1 ppm of HCHO gas and 126.8\% at 50 ppm.

3.4. Visible–Activated Ammonia Gas Sensors

In 2021, Huang et al. demonstrated a copper phthalocyanine–loaded zinc oxide (CuPc/ZnO)–based NH\(_3\) gas sensor fabricated using a microwave–assisted hydrothermal synthesis method [104]. The responsivity of the CuPc/ZnO gas sensor with NH\(_3\) gas was improved under red light irradiation (\(\lambda = 600\) nm to 622 nm). The red–light irradiation effect promoted the desorption of oxygen on the ZnO surface, making the depletion layer thin. In addition, the photoelectrons generated by red light increased the electron concentration in ZnO, resulting in more oxygen ions that interact with the NH\(_3\) molecules. Figure 9a shows the NH\(_3\) gas response of the CuPc/ZnO gas sensor and the pure ZnO gas sensor. The concentration of injected NH\(_3\) gas was 80 ppm, and the red light had an intensity of 0.15 W/cm\(^2\). The pure ZnO gas sensor and the CuPc/ZnO gas sensor showed a further decrease in resistance when irradiated with red light than in the dark. On the other hand, the CuPc/ZnO gas sensor showed improved response and recovery times, as well as a response to NH\(_3\) gas compared to the pure ZnO gas sensor (Figure 9b). The red–light illumination effect reduced the barrier height of the CuPc/ZnO gas sensor to enhance the electron mobility. The response time and recovery time values of the pure ZnO were measured at 31 s and 18 s, respectively. On the other hand, the CuPc/ZnO gas sensor exhibited a response time value of 20 s and a recovery time value of 10 s. Figure 9c shows the response behavior of the CuPc/ZnO gas sensor and the pure ZnO gas sensor to various gases. The selectivity of CH\(_3\)OH, C\(_2\)H\(_5\)OH, C\(_3\)H\(_7\)OH, H\(_2\), CO, and CH\(_4\) at 80 ppm was investigated. The response of the CuPc/ZnO gas sensor irradiated with red light to NH\(_3\) gas was approximately 12, whereas the responses to the remaining gases were less than five.

For achieving high responsivity of NH\(_3\) gas sensor, Shao et al. used silver phosphate (Ag\(_3\)PO\(_4\)) as a photocatalytic [105]. The Ag\(_3\)PO\(_4\) NPs have efficient separation of electron–hole pairs with visible light illumination. The calculated bandgap and intrinsic absorption long wavelength limit of Ag\(_3\)PO\(_4\) NPs synthesized by the precipitation method was 2.24 eV and 554 nm, respectively, which is less energy than the white LED with a wavelength range of 440 nm to 470 nm. Figure 9d shows the response of the Ag\(_3\)PO\(_4\) NPs gas sensor to NH\(_3\) gas with concentrations ranging from 10 to 300 ppm. Dark1 and Light1 indicate the responses of the Ag\(_3\)PO\(_4\) NPs gas sensor to NH\(_3\) gas with and without visible light illumination, respectively. Owing to the visible light activated Ag\(_3\)PO\(_4\) NPs, the resistance change in the Ag\(_3\)PO\(_4\) NPs gas sensor was larger under visible light illumination. In addition, when the Ag\(_3\)PO\(_4\) NPs were exposed to light, they could corrode and generate metal silver on the surface, affecting the gas sensor’s performance. Dark 2 is the response of the Ag\(_3\)PO\(_4\) NPs gas sensor in the dark, which was previously exposed to visible light to NH\(_3\) gas. The response of Dark 2 was similar that in Dark 1 because of the suppressed photocorrosion of Ag\(_3\)PO\(_4\) by adjusting the visible light exposure time. The LR is the calculated Ag\(_3\)PO\(_4\) NPs gas sensor response under visible light without NH\(_3\) gas. Figure 9e shows the selectivity characteristics of the Ag\(_3\)PO\(_4\) NPs gas sensor. The Ag\(_3\)PO\(_4\) NPs gas sensor was exposed to IPA, methanol, ethanol, gases, and NH\(_3\) at 100 ppm each. The response of the Ag\(_3\)PO\(_4\) NPs gas sensor to NH\(_3\) gas was highly selective, 1.55 and 1.8 in the dark and visible light conditions, respectively. In addition, the response of mixed NH\(_3\)–based gases were investigated (Figure 9f). The Ag\(_3\)PO\(_4\) NPs gas sensor has strong selectivity for NH\(_3\) molecules as a result of its response to NH\(_3\) based mixed gases.
Visible light was irradiated to shorten the recovery time of organic material–based gas sensors. Lin et al. reported a NH$_3$ gas detector with a vertical diode by using poly-[4,8-bis[5-(2-ethylhexyl)-2-thienyl]benzo[1,2-b:4,5-b']dithiophene-2,6-diyl] [2-(2ethyl-1-oxoethyl)thieno[3,4-b]thiophenediyl]] (PBDTTT–C–T) [106]. The PBDTTT–C–T gas detector based on the organic materials was irradiated with various wavelengths of visible light to compensate for the slow recovery time. On the other hand, the recovery time was improved when the PBDTTT–C–T gas sensor was irradiated with blue light because of the current compensation effect. Figure 9g shows the fabrication process of the PBDTTT–C–T gas sensor and the NH$_3$ gas detection system. ITO with improved surface hydrophilic characteristics through the oxygen plasma treatment was used as a substrate. Subsequently, poly(4-vinylphenol) (PVP) for the insulating layer was deposited by spin coating. Poly(3-hexylthiophene–2,5-diyl) (P3HT) was spin–coated for the adhesion of polystyrene (PS) nano–spheres. The prepared samples were immersed in a PS solution to form polystyrene (PS) nano–spheres. Al was deposited over the entire surface using the evaporation method, and the PS spheres were removed using 3M Scotch tape.
to induce porous patterning on the sample. The exposed PVP was removed by oxygen plasma etching. Finally, PBDTTT–C–T was deposited using the blade coating method. The PBDTTT–C–T gas sensor was mounted in an opaque box, and the wavelengths of the LED used were 465, 620, and 730 nm. Figure 9h shows the response of the PBDTTT–C–T gas sensor to 300 ppb of NH$_3$ gas. After NH$_3$ gas was injected into the PBDTTT–C–T gas sensor for 30 s, it was irradiated with the LED. As a result, the recovery time was improved when the PBDTTT–C–T gas sensor was irradiated with LED light. In addition, the enhanced response to light at 465 nm was attributed to the stronger irradiance than the other two LEDs. Figure 9i shows the response of the PBDTTT–C–T gas sensor to NH$_3$ at concentrations from 100 to 2000 ppb. The stability of the PBDTTT–C–T gas sensor was confirmed by performing at least three tests with different NH$_3$ gas concentrations. Table 1 summarizes the sensing performance of photo-activated gas sensors for NO, NO$_2$, HCHO, and NH$_3$ based on UV and visible light.

### Table 1. Comparison of sensing performance of the photo-activated gas sensor.

| Materials       | Light                  | Target Gas | Limit of Detection | Sensitivity | Ref      |
|-----------------|------------------------|------------|--------------------|-------------|----------|
| TiO$_2$@NGQDs   | UV ($\lambda$ = 365 nm) | Nitric oxide | 10 ppm            | ~31.1% at 100 ppm | [85]     |
| Cu–TCA/TiNCs    | UV ($\lambda$ = 365 nm) | Nitric oxide | 140 ppb          | ~124% at 50 ppm | [86]     |
| ZNO NW          | UV ($\lambda$ = 325 nm) | Nitric dioxide | 20 ppb         | ~708% at 1 ppm | [87]     |
| MoS$_2$         | UV ($\lambda$ = 365 nm) | Nitric dioxide | 5 ppm           | ~3% at 1 ppm | [88]     |
| CNT             | UV ($\lambda$ = 365, 275 nm) | Nitric dioxide | 1 ppm | N/A | [89]     |
| Au–ZnO POH      | UV ($\lambda$ = 365 nm) | Formaldehyde | 50 ppm          | ~7.6 at 100 ppm | [90]     |
| SnO$_2$@TiO$_2$ | UV ($\lambda$ = 365 nm) | Formaldehyde | 100 ppb         | ~32.5% at 10 ppm | [91]     |
| NiS/Ni–ZnO      | UV ($\lambda$ = 365 nm) | Formaldehyde | 2 ppm           | ~330% at 10 ppm | [92]     |
| PANI/TiO$_2$    | UV ($\lambda$ = 365 nm) | Ammonia     | 50 ppb          | ~109.87% at 1 ppm | [93]     |
| rGO/TiO$_2$/Au  | UV ($\lambda$ = 365 nm) | Ammonia     | 2 ppm           | ~8.9% at 50 ppm | [94]     |
| 2DPI/In$_2$O$_3$| UV ($\lambda$ = 365 nm) | Ammonia     | 50 ppb          | ~6.5 at 1 ppm | [95]     |
| Au/ZnO          | Vis ($\lambda$ = 382, 439, 525 nm) | Nitric oxide | 1 ppm | ~12 at 10 ppm, blue | [96]     |
| SnO$_2$/GQDs    | Vis ($\lambda$ ≥ 420 nm) | Nitric oxide | 600 ppb         | N/A | [97]     |
| α–Fe$_2$O$_3$/g–C$_3$N$_4$ | Vis ($\lambda$ ≥ 400 nm) | Nitric oxide | 600 ppb | N/A | [98]     |
| In$_2$O$_3$ NW  | Vis ($\lambda$ = 400 to 700 nm) | Nitric dioxide | 10 ppb       | ~750% at 5 ppm | [99]     |
| Au/MoS$_2$      | Vis ($\lambda$ = 530 nm) | Nitric dioxide | 10 ppb | ~8.1 at 1 ppm | [100]   |
| rGO@ZnO        | Vis, white LED         | Nitric dioxide | 50 ppb       | ~2.31 at 50 ppm | [101]   |
| HoFeO$_3$       | Vis ($\lambda$ = 660 nm) | Formaldehyde | 80 ppb         | ~78% at 100 ppm | [102]   |
| MoS$_2$/rGO     | Vis ($\lambda$ > 420 nm) | Formaldehyde | 20 ppb         | ~64% at 10 ppm | [103]   |
| CuPc/ZnO       | Vis ($\lambda$ = 600 to 622 nm) | Ammonia | 800 ppb | ~12 at 80 ppm | [104]   |
| Ag$_3$PO$_4$ NP | Vis ($\lambda$ = 400 to 800 nm) | Ammonia | 10 ppm | ~45% at 10 ppm | [105]   |
| PBDTTT–C–T     | Vis ($\lambda$ = 465, 620, 730 nm) | Ammonia | 100 ppb | ~22 at 300 ppb, blue | [106] |

### 4. Conclusions

This review reported various strategies for producing gas detectors activated by ultraviolet and visible light that have been reported in recent years. Research on photo-activated gas detectors using metal oxide semiconductors, TMDs, and carbon nanotubes has been reported. Techniques, such as porous structures, heterojunctions, and surface defects, improve the responsivity, selectivity, response, and recovery time of photo-activated gas detectors. In addition, photo-activated gas detectors are classified according to the type of detectable gas, such as nitric oxide, nitric dioxide, formaldehyde, and ammonia gas. Photo-activated
gas detectors, with external light illumination, replaced conventional high—temperature gas detectors, providing a technological foundation for low—power consumption and miniaturization. On the other hand, despite these advantages, photo—activated gas sensing technology still has technical barriers to overcome, and technology development strategies for advancing high—performance light—activated gas detectors are needed.

1. Photo—activated gas detectors use a specific wavelength of light to increase selectivity for a target gas. However, most of the photoactive gas detector performance has been reported in an environment where the variables are controlled, such as temperature and humidity. Therefore, to commercialize photoactive gas detectors in the industry, measurements should be performed in an environment with complex variables, including detecting a target gas contained in a mixed gas.

2. The photo—activated gas detection system should reduce its weight and size for portability and miniaturization. The presence of light sources that irradiate ultraviolet or visible light has expanded the use of photo—activated gas detection systems. In addition, the integration of existing systems, such as computers and smartphones, should be considered. Therefore, it is necessary to re—examine the photo—activated gas detection system using a new structural design.

3. The sustainability and stability of photoactive detectors need to be reviewed further. Gas detectors are attracting attention as a safety system in various fields, such as factories and hospitals. To monitor a gas in real time, it is necessary to ensure the overall durability and reliability of the photoactive gas detectors.

4. The presence or absence of a disease could be diagnosed through the concentration of a target gas detected in human exhalation. On the other hand, it is necessary to detect low concentrations of gases precisely to distinguish between healthy and diseased people. The photoactive gas detectors for diagnosing disease require an improved response to low—concentration gases.

In spite of the aforementioned technical limitations, research and technological development of photo—activated gas detectors are actively progressing. Photo—activated gas detectors have potential advantages for gas detection and are believed to be core electronics for industrial stabilization in the future.

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