Theoretical and Experimental Investigation on SPR Gas Sensor Based on ZnO/Polypyrrole Interface for Ammonia Sensing Applications

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Abstract
This work includes the exploitation of the laboratory-assembled SPR technique for the application of gas sensors at room temperature. The refractive index change at the interface of ZnO/polypyrrole with adsorption of gases (NH3) is the basis of the SPR gas sensor. The theoretical simulations were done to find out the optimum thickness of ZnO and polypyrrole composite films for sharp SPR reflectance values. Theoretical SPR curves obtained by changing the value of the thickness of gold nanoparticle film and incident wavelength are also presented in the manuscript. Experimental studies were done to validate the theoretical studies and discussions were done about the interaction of NH3 gas with prism/Au/ZnO/polypyrrole system. Here, ZnO/polypyrrole multilayer structure is the sensing layer to develop a highly efficient SPR-based NH3 gas sensor. The outcome of these results validates the significance of the SPR technique for the application of interaction of surface adsorbed analytes, with the interface of dielectrics and sensing material.

Keywords  Gas sensor · Surface plasmon resonance · ZnO/polypyrrole composite

Introduction
Research community has always been putting efforts to develop highly sensitive and efficient gas sensors in order to keep the environment and work places safe from any accidental leakage at domestic and industrial production [1, 2]. At present, we have various technologies of gas sensing which include conductometric and optical sensing technologies. Out of which, conductometric sensing technology has various disadvantages like requirement of elevated temperature demanding high power consumption and poor selectivity. Hence, we need to think for the preference of highly efficient and selective gas sensor based on optical sensing technologies [3]. The major advantage of optical gas sensor is due to its ability of operation, which use less power, at room temperature [4]. A lot of optical techniques are available for sensing purposes such as FTIR [5], UV–Vis photo spectrometry [6], ellipsometry [7], and surface plasmon resonance technique [8]. Out of all the known techniques, optical gas sensors based on SPR have enormous advantages like simple sample preparation, operation at room temperature, lower detection limit, high stability and sensitivity, and non-destructive [9]. The surface plasmon resonance (SPR) technique is one of the oldest techniques for the application in gas sensing and researchers have exploited it for gas sensing applications [10–12]. But, results were lacking in terms of poor response and complicated and bulky setup. Therefore, the very first step to develop a gas sensor, is to optimize the thickness of the sensing layer. The gas sensing results based on SPR in old articles uses a bulky setup (Kretschmann configuration) in which there is a separate laser for the excitation and huge spectrometer table for varying the angle of incidence. This makes the setup bulky not suitable for practical applications. In our work, a compact and table-top SPR setup has been exploited in which excitation source, i.e., laser and source holder (i.e., spectrometer table) are arranged in a small compartment. The technical details are discussed in the experimental section. The present work is initiated with theoretical simulation for optimization of thickness of ZnO layer and polypyrrole layer separately. SPR technique is a very sensitive technique which can be used for sensing of minute changes near the boundary interface of dielectric with the metal [13]. Thus, the variance in
the reflectance values can be related for the indication of a particular gas in the vicinity of the interface showing the change of the refractive index.

Now, the focus in this work presented here is on the detection of highly toxic and dangerous ammonia (NH$_3$) gas. NH$_3$ gas is produced from as a waste product from livestock or emanation from industry and automobile. Many efforts are continuing in the aim of detection of NH$_3$ gas by research community [14, 15]. The required detection limit of ammonia gas is 25 ppm as it is toxic to both human and animal life (i.e., safe level is 25 ppm for 8-h long-term exposure). This increased to 35 ppm for short-term exposure (15 min) [16]. It is always better to detect any kind of toxic gas at the earliest. Hence, it is reported that 25 ppm is the safe limit for ammonia exposure but detection of this highly toxic gas at low concentration is highly recommended. Also, it is crucial to detect ammonia at low concentrations for monitoring releases in the environment from chemical industries, automobiles, refrigeration, and agricultural (fertilizer and livestock) systems [17]. The present focus of the researchers is to develop an efficient gas sensor to sense very low concentration of NH$_3$ leaks (≤ 5 ppm) [18]. There are very few reports available on SPR gas sensors focused for the detection of NH$_3$ gas [19, 20]. But, they all reported poor sensitivity and aim to detect higher concentration of ammonia (> 25 ppm). Maciak et al. have utilized polyaniline sensing layer-based SPR spectroscopy technique to monitor ammonia vapors for a lower concentration value of 32 ppm [19]. Dolbec and El Khakani have also detected higher concentration of ammonia using a different sensing layer, i.e., Nafion/WO$_3$ [20].

This has been previously discussed that gas sensing using the SPR technique requires an optimized sensing layer for detection. Hence, choosing a suitable material and its optimization is highly crucial for the development of the sensor. Therefore variation of refractive index in the sensing layer after the exposure of target gas on it is in direct relation to the detection sensitivity of the analytes interacting with it. For the past few decades, semiconductor metal oxides possess suitable properties for sensing applications, i.e., for sensing various toxic gases, and among all the explored metal oxides in the application as the sensing material, ZnO is the best choice. ZnO has suitable semiconducting, piezoelectric, and pyroelectric properties [21]. Another class of materials that recently has been explored is the conducting polymers due to their good electrical and optical properties [22]. Enormous articles report the gas sensing results using conducting polymers due to high sensitivities and short response time at room temperature exhibited by them [22]. Among the various exploited conducting polymers for gas sensing applications, polypyrrole (PPy) have more advantages. The major advantages include easy and low-cost fabrication of PPy thin film with short response time, and room temperature sensing. This may pave the way for the fabrications of an SPR gas sensor for low-level detection of ammonia gas having high sensitivity and efficiency.

The present manuscript systematically analyses the characteristics of highly sensitive and room temperature-operated NH$_3$ optical gas sensors. Firstly, an appropriate and suitable technique for gas sensing, i.e., SPR, has been chosen due to the above-discussed advantages. Secondly, an effort has been made to incorporate a suitable material, i.e., PPy with well-established metal oxide sensing layer, i.e., ZnO to form a multilayer structure of PPy and ZnO. Theoretical simulations are done to optimize the thicknesses of PPy and ZnO for high response and sensitivity. The change in refractive indices of the ZnO/polypyrrole composite multilayer thin film structure deposited at their optimized value of thickness on gold-coated prisms is examined using the SPR technique with varying concentrations of toxic NH$_3$ gas. This leads to the development of a highly sensitive and stable sensor having a linear response within a particular range of concentration of NH$_3$ gas. The novelty of this manuscript is the development of room-temperature-operated NH$_3$ gas sensors with low response time and limit of detection.

### Theoretical Simulation Details

The behavior of intensity of reflected light with an angle of incidence (angular interrogation mode) can be described by Fresnel’s equations where light is reflected from different interfaces (metal/dielectric, prism/metal, dielectric/dielectric interfaces). The theoretical values of reflectance for a single-layer (prism/metal/air) and double-layer (prism/metal/dielectric/air) systems have been applied for the determination of the refractive index of gold (metal) and dielectric layer, respectively.

#### One-Layer System (Prism/Metal/Dielectric (Air))

Let $n_i$ (i = 0, 1, 3) be the values of refractive index for any one of the media (prism/metal/dielectric), and $\theta_i$ is the corresponding value of incident angle at the prism/metal/air boundary of these media; here we will use the subscripts as 0 corresponding to the prism, as 1 corresponding to metal, and 3 as for the dielectric (air) media. The Fresnel’s reflection coefficient for a p-polarized light passing from ith medium to kth medium is given as [26]:

$$r_{ik} = \frac{n_i \cos \theta_i - n_k \cos \theta_k}{n_i \cos \theta_i + n_k \cos \theta_k}$$  \hspace{1cm} (1)
The z-component of the propagation constant in $ith$ medium is given by [23]:

$$k_{zi} = \frac{2\pi n_i \cos \theta_i}{\lambda} = \frac{2\pi \sqrt{\varepsilon_i - \varepsilon_0 \sin^2 \theta}}{\lambda} \quad (2)$$

Since, dielectric constant, $\varepsilon = (\text{refractive index, } n)^2$ and using Eqs. (1) and (2), we have,

$$r_{ik} = \left( \frac{k_i - k_k}{\varepsilon_i + k_i \varepsilon_k} \right) \left( \frac{k_i + k_k}{\varepsilon_i + k_i \varepsilon_k} \right) \quad (3)$$

where $\varepsilon_i$ and $\varepsilon_k$ are the dielectric constants of the $ith$ and $kth$ medium, and $\varepsilon_0$ is the dielectric constant for the prism.

So, the reflectance for single layer system (prism/metal/dielectric (air)) is given by [26]:

$$R_{013} = \left| \frac{r_{01}r_{13} \exp(2ik_{13}d_1)}{1 + r_{01}r_{13} \exp(2ik_{13}d_1)} \right|^2 \quad (4)$$

where subscripts “0,” “1,” and “3” refer to the prism, the metal layer, and dielectric (air) media, respectively. “$d_1$” is the thickness of the metal thin film. “$r_{01}$” and “$r_{13}$” are Fresnel’s reflection coefficients and z components of propagation constant as given by Eqs. (3) and (2), respectively. The reflectance is calculated for the single-layer system (prism/metal/dielectric (air)) by Eq. (4) using known values for L, $\theta$, and $\Sigma$, and the value of complex dielectric constants of the metal layer may be obtained.

**Double-Layer System (Prism-Au-Dielectric-Air)**

For the realization of gas (optical) sensors, a suitable sensing layer (dielectric) has to be integrated with the metal layer, which should be sensitive to the stimulus under consideration. Also, to probe the property of any unknown material (dielectric), it has to be in the vicinity of the metal layer. Therefore, the study of a double layer system consisting of prism/metal/dielectric (air) is important. Using Fresnel’s equation for the calculation of the reflectance of this double layer system is as follows [24]:

$$R_{0123} = \left| \frac{r_{01} + r_{123} \exp(2ik_{13}d_1)}{1 + r_{01}r_{123} \exp(2ik_{13}d_1)} \right|^2 \quad (5)$$

where

$$r_{123} = \frac{r_{12} + r_{23} \exp(2ik_{23}d_2)}{1 + r_{12}r_{23} \exp(2ik_{23}d_2)} \quad (6)$$

and $r_k$ is the Fresnel’s reflection coefficients given by Eqs. (1) and (3). Here, subscript “2” refers to the deposited ZnO/polypyrrole as sensing material and “$d_2$” is its depth. Considering the dielectric constant of the sensing layer ($\varepsilon_2$) as the fitting parameter, the SPR reflectance obtained for the prism/metal/dielectric/dielectric (air) system is fitted with Eq. (5) and the complex dielectric constant of the sensing layer is obtained.

**Experimental Details: Fabrication of SPR-Based NH$_3$ Gas Sensor**

In this work, the multilayer structure of the films was prepared. We deposited the gold (Au) thin film of optimized value on the surface of a glass prism by the thermal evaporation method on the parameters reported in our previous report [27]. After this, ZnO film is coated on Au-coated prism. The sol–gel method was utilized to synthesize ZnO nanoparticles and then they were put in thin-film form by using the spin coating technique [28]. Finally, polypyrrole (PPy) thin films were coated over this structure. PPy nanoparticles were fabricated by the method of chemical polymerization and their films were prepared by spin coater [28].

In our work, a compact and table-top SPR setup has been exploited in which excitation source, i.e., laser and source holder (i.e., spectrometer table) are arranged in a small compartment. The setup has been developed in the lab independently and technology has been transferred to M/s Optiregion. The technical details of the setup used are discussed. Kretschmann configuration is used for the excitation of surface plasmon (SP) on the prism/gold interface by using a BK-7 glass prism ($n_p = 1.517$) and the optimized thickness of Au film with the help of an SPR measurement system. For the measurement of the SPR reflectance, a solid-state laser (p-polarized and of wavelength 683 nm) was used for the irradiation of the prism/Au/ZnO/PPy/air system and the reflected light (which is a function of incident angle) was monitored. The schematic of our SPR gas (optical) sensor, as shown in Fig. 1, uses a...
cylindrical cell for the target gas attached to the prism deposited with the gold (Au) and the target gas sensitive material’s coating (prism/Au/ZnO/PPy/air) is placed in contact with this cylindrical gas cell so that the target gas molecules can interact with the deposited gas sensitive material interface (ZnO/PPy). A mechanical rotary pump was used for creating a vacuum. Static and dynamic mode measurements were done. The ammonia (NH₃) target gas of a specific concentration value was inserted into this gas cell with calibrated needles connected to the inlet valve. In the static mode, we insert the ammonia gas inside the gas cylindrical cell for the full angle variation, and the SPR reflectance plot was recorded with an optical power meter. The dynamic measurements were done with the system of prism/Au/ZnO/PPy/air, where we get a minimum value of SPR reflectance ($R_{\text{min}}$). We then record the intensity of the reflected light keeping incident light at a fixed angle (as a function of time) with the help of a CCD camera interfaced with a computer. The change in intensity is measured for the various concentrations of the ammonia gas when it is introduced into the gas cell and as well as for the outgoing of the ammonia gas. We use the rotatory pump for the ejection of ammonia gas for the recovery time measurement of our gas sensor system of (prism/Au/WO₃/air), which then filled with the fresh clean air for reference.

Results and Discussion

Theoretical Simulation Studies

The Varying Thickness of Gold Thin Film

SPR reflectance curves by varying the thickness of Au in Eq. (4) are depicted in Fig. 2. SPR reflectance sharpest value is observed for 40 nm thickness of Au having minimum FWHM.

SPR Reflectance Plots of the System Prism/Au/Air, Prism/Au/ZnO/Air, and Prism/Au/ZnO/PPy/Air

A schematic of the two- and three-layer configurations used is shown in Fig. 3a. Theoretical simulation of the SPR reflectance plots by increasing the number of layers is shown in Fig. 3b (i.e., prism/Au/air, prism/Au/ZnO/air, and prism/Au/ZnO/PPy/air). The angle of resonance shifts towards higher values by increasing the number of layers from the ZnO/air interface to the ZnO/PPy/air interface.

The Varying Thickness of ZnO

Figure 4 shows the SPR reflectance plots for the system of prism/Au/ZnO/PPy/air by changing the thickness of ZnO. The variation of resonance angle, minimum reflectance, and FWHM has been presented in Fig. 5a–c, respectively. All the parameters increase with the increase in thickness of ZnO. SPR reflectance curve having minimum FWHM is chosen for experimental studies. Hence, 100 nm ZnO SPR has minimum FWHM (or absorption losses) is the optimized thickness of the ZnO layer.

The Varying Thickness of Polypyrrole Thin Film

Figure 6 shows the plots of SPR reflectance of the gas sensing system of prism/Au/ZnO/PPy/air by changing the thickness of PPy.

The variation of resonance angle, minimum reflectance, and FWHM are presented in Fig. 7a–c, respectively. All the parameters increase linearly with the increase in thickness

![Fig. 2 Theoretical SPR reflectance plots the system of prism/Au/air by changing the thickness of the Au layer](image-url)
of PPy. SPR reflectance curve having minimum FWHM is chosen for experimental studies. Hence, 150 nm PPy SPR has minimum FWHM (or absorption losses) that is the optimized thickness of the PPy layer.

**Optimizing ZnO and PPy Thicknesses**

In our previous studies, we have varied a single parameter (i.e., thicknesses of ZnO and PPy separately). Single parameter screening may not provide the best choice. For optimizing ZnO and Polypyrrole thickness, a 2D heat map with x and y as ZnO and polypyrrole thickness is drawn. According to the theoretical simulations, SPR reflectance curves were obtained by varying the value of thickness for ZnO first (keeping the thickness of PPy constant) and secondly varying the value of the thickness of PPy (keeping the thickness of ZnO constant). Since FWHM is a key parameter to optimize the thickness of ZnO and PPy for a sharp SPR reflectance curve. Hence, a heat map is generated keeping the x and y-axis fixed for the thickness of PPy and ZnO, respectively, and the z-axis fixed for FWHM using Microsoft Excel as shown in Fig. 8.

Theoretical simulations were done for varying values of thickness of PPy and ZnO thin films. According to the color contrast, the best choice of thickness for PPy and ZnO thin film is confirmed by the bright yellow color, i.e., 100-nm-thick ZnO and 150-nm-thick PPy results in the sharpest SPR reflectance curve.

**Varying Incident Wavelength**

SPR reflectance plots of the optimized system of prism/Au/ZnO/PPy/air with the 100 nm ZnO and 150 nm PPy are shown in Fig. 9. With the increase in the wavelength of the incident light, the resonance angle shifts to a lower value. FWHM of the SPR curve for 355 nm incident wavelength is maximum which decreases with an increase in wavelength and is found to be minimum for 633 nm wavelength. After 633 nm wavelength, the SPR curves become attenuated. The experimentally obtained SPR reflectance curves are shown by dotted lines and theoretically simulated curves by the solid lines.
Theoretical simulations were also done on the system of prism/Au/ZnO/PPy/air by varying the refractive index of the exposed sensing material, which is in contact with the ZnO/PPy interface on exposure to NH$_3$ gas of different concentrations. The refractive index is sequentially varied and SPR reflectance curves are measured. It is observed from Fig. 10a that ATR curves shift towards the right, i.e., resonance angle increases with the increase of the effective refractive index of the sensing material. The linear change of the angle of resonance and minimum reflectance with an increase in the effective refractive index is shown in Fig. 10b, c, respectively. This confirms the possibility of developing a highly sensitive sensor utilizing the system of prism/Au/ZnO/PPy/air as a detector for the Ammonia (NH$_3$) gas with varying concentrations.
Experimental Studies

The data of SPR reflectance obtained for the system of prism/Au/ZnO/PPy/NH$_3$ when exposed to changing concentration of NH$_3$ gas (0 to 200 ppm) is plotted in Fig. 11. A continuous change in $\theta_{\text{SPR}}$ towards higher values of angles (from 54.9 to 95.3°) is observed with the incremental change of the concentration of NH$_3$ gas from 1 to 200 ppm (Fig. 11).

Figure 12a, b depict the exponential increment of the values of $\theta_{\text{SPR}}$ and $R_{\text{min}}$ for our gas sensing system of prism/Au/ZnO/PPy/NH$_3$ when we vary the concentration of NH$_3$ gas from 0 to 200 ppm (Fig. 11). Figure 12a, b depict the exponential increment of the values of $\theta_{\text{SPR}}$ and $R_{\text{min}}$ for our gas sensing system of prism/Au/ZnO/PPy/NH$_3$ when we vary the concentration of NH$_3$ gas from 0 to 200 ppm. The observed change in the SPR data is due to the variation of the effective refractive index of the ZnO/PPy interface when the ammonia gas is adsorbed at various concentrations. As evident from Fig. 12a, b, there is a linear increase in $\theta_{\text{SPR}}$ and $R_{\text{min}}$ to 10 ppm concentration of the ammonia (NH$_3$) gas. As the concentration of the ammonia gas increase, the values of $\theta_{\text{SPR}}$ and $R_{\text{min}}$ saturates. This is due to the fact that with the high ammonia gas concentration, there is no appreciable change in the effective refractive index which is reflected in the nonlinear variation of $\theta_{\text{SPR}}$ and $R_{\text{min}}$. We can also see that the FWHM of SPR response of the sensing system shows the same variation as that of $\theta_{\text{SPR}}$ and $R_{\text{min}}$ (Fig. 12c), showing that the losses increase continuously until 10 ppm concentration is reached.
The experimental data for the SPR reflectance measured in the presence of NH₃ gas of various concentrations has been fitted theoretically with the help of Fresnel equations as mentioned earlier, and the estimation of the values of \( n_i \) and \( k_i \) were done. The variation of the effective refractive index of the sensing layer of the ZnO/PPy interface with the increasing concentration of adsorbed NH₃ gas is shown in Fig. 13a (calibration curve). The refractive index was found to increase linearly to 10 ppm concentration as shown in Fig. 13b. The graph is fitted linearly and the value of sensitivity is found from the slope of the calibration curve, i.e., \( 3.15 \times 10^{-3} \) RIU/ppm.

As shown in Fig. 13a, the variation of refractive index with the concentration of target gas saturates after 50 ppm. It can be evident from Fig. 13b that the estimated value of the refractive index for a lower concentration of target NH₃ gas, i.e., till 10 ppm results in the value of resonance angle similar to the value obtained by theoretical simulation. For a better comparison between theoretical and experimental results, a table has been formulated. The table is shown below:

| NH₃ Concentration (ppm) | Resonance Angle Deviation (°) |
|------------------------|-----------------------------|
| 1                      | 0.000                        |
| 5                      | 0.002                        |
| 10                     | 0.003                        |
| 20                     | 0.005                        |
| 50                     | 0.008                        |
| 100                    | 0.010                        |
| 200                    | 0.012                        |

As evident from Table 1, the deviation in resonance angle from theoretical value is higher with increasing concentration of target NH₃ gas. This may be due to higher adsorption of NH₃ gas molecules at the surface of sensing ZnO material resulting in a higher shift in resonance parameters of the SPR reflectance curve.

When NH₃ gas is present in the bulk media, its adsorption on the ZnO/PPy interface leads to the surface plasmon propagation distortion and so the losses in the gas sensing system keep on increasing as depicted from plots of the increasing FWHM of the SPR reflectance curves. We find the important fact that the gas sensing system of prism/Au/ZnO/PPy shows good sensitivity and high linearity over a wide good range (1 to 10 ppm) of NH₃ gas.

Figure 14a depicts the dynamic response for the system of prism/Au/ZnO/PPy upon exposure with the changing concentration of NH₃ gas from 0 to 200 ppm and the incident angle is kept at a value of \( \theta = 54.9° \). Here we use a CCD for measuring the changes in the reflectance of our gas sensing system. The gas sensing system shows a continuous increase in the sensitivity (change in reflectance) with the change in concentration of NH₃ gas from 1 to 200 ppm kept at room temperature (Fig. 14a). The calibration curve of the SPR gas sensor is also plotted as shown in Fig. 14b. Figure 14b shows that there is a saturation of change in reflectance after 10 ppm concentration. A linear increase in the response, i.e., a change in reflectance with an increase in the concentration of NH₃ gas over the range of 1 to 10 ppm, is shown in Fig. 14c. The variation in sensing response (\( \Delta R \)) is similar to that obtained for \( R_{\min} \) and \( \theta_{SPR} \) with NH₃ gas concentration. The sensitivity of the fabricated SPR sensor prism/Au/SnO₂ is about 0.112/ppm for NH₃ concentration varying from 1 to 10 ppm (Fig. 14c). The obtained result represents the development of a sensitive SPR gas sensor for the efficient detection of NH₃ gas.
Fig. 10  a SPR reflectance plots of the system of prism/Au/ZnO/PPy/air for varying effective refractive index, b linear increase of resonance angle, and c the minimum reflectance with changing the effective refractive index
Fig. 11  Experimental data obtained for the system of prism/Au/ZnO/PPy/NH₃ SPR reflectance plots upon exposure of NH₃ gas with increasing concentration. The theoretical value is also plotted for comparison.
Fig. 12  Plots of a SPR angle of resonance ($\theta_{\text{SPR}}$), b $R_{\text{min}}$, and c FWHM of the SPR sensing system with variation in the concentration of NH$_3$ gas.
A specially designed gas cell has been integrated with the indigenously developed SPR set up for the detection of various toxic and harmful gases. SPR system is demonstrated successfully for detection of NH$_3$ gas using the interface of ZnO and PPy. Surface plasmon resonance gas sensor system of prism/Au/ZnO/PPy has been developed using the optimized thickness of ZnO and PPy obtained by theoretical simulation for the detection of ammonia (NH$_3$) gas. The 100 nm thin ZnO film and 150 nm thin PPy film were deposited which exhibit the sharpest SPR reflectance curve and

### Table 1

| Theoretical | Experimental |
|-------------|--------------|
| Resonance angle | Refractive index | Resonance angle | Refractive index |
| 55.68 | 1.373 | 55.15 (0 ppm) | 1.373 |
| 58.43 | 1.383 | 58.34 (1 ppm) | 1.388 |
| 60.46 | 1.393 | 63.66 (5 ppm) | 1.397 |
| 64.05 | 1.403 | 75.55 (10 ppm) | 1.409 |

**Fig. 13** a Variation of the effective index of ZnO/PPy interface when the NH$_3$ gas gets adsorbed, with the increase of its concentration and b variation of the refractive index till 10 ppm concentration

### Conclusion

A specially designed gas cell has been integrated with the indigenously developed SPR set up for the detection of various toxic and harmful gases. SPR system is demonstrated successfully for detection of NH$_3$ gas using the interface of ZnO and PPy. Surface plasmon resonance gas sensor system of prism/Au/ZnO/PPy has been developed using the optimized thickness of ZnO and PPy obtained by theoretical simulation for the detection of ammonia (NH$_3$) gas. The 100 nm thin ZnO film and 150 nm thin PPy film were deposited which exhibit the sharpest SPR reflectance curve and
are found useful for the successful detection of NH$_3$ gas. The SPR gas sensor shows a fast response (1 s) and good sensitivity ($3.15 \times 10^{-3}$/ppm) towards NH$_3$ gas over a wide concentration (1 to 10 ppm). The dynamic response was also observed and the sensitivity was estimated from the calibration curve, i.e., 0.112/ppm. Thus, efficient SPR gas sensors are realized in the present work with enhanced response characteristics.

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**Author Contribution** Ajay Pratap Singh Gahlot: methodology, editing, and conceptualization; Ayushi Paliwal: methodology, writing–original draft; Avinashi Kapoor: supervision, writing–review and editing.
Availability of Data and Material  The data sets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics Approval  The submitted work should be original and should not have been published elsewhere in any form or language.

Consent to Participate  Not applicable.

Consent for Publication  Not applicable.

Competing Interests  The authors declare no competing interests.

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