Lab on a Chip



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Cite this: Lab Chip, 2023, 23, 3518

Received 16th December 2022, Accepted 26th June 2023

DOI: 10.1039/d2lc01149b

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1. Introduction

Hydrogen is a renewable green energy source that plays an irreplaceable role in the fields of the petrochemical industry, metallurgy, rocket fuel production, and medical diagnostics and therapeutics.^{1,2} However, tiny-sized hydrogen molecules rapidly leak out *via* small holes and fissures, and hydrogen gas is combustible and explosive at concentrations of more than 4%. Therefore, a secure and rapid method for tracing hydrogen leaks (ppb-level leakages) in storage tanks, transport pipelines, and working areas is vital and urgent.^{1–3} Different types of analytical instrument, such as thermal conductivity measurements,^{4,5} ultraviolet (UV) absorption spectroscopy,⁶ and chemo-resistive gas sensors,^{7,8} have been abundantly used for monitoring hydrogen concentrations in previous reports. Despite their favorable response and wide gas detection range for hydrogen monitoring, these approaches generally

Fiber-tip Fabry–Pérot interferometer with a graphene–Au–Pd cantilever for trace hydrogen sensing†

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The widespread utilization of hydrogen energy has increased the demand for trace hydrogen detection. In this work, we propose a fiber-optic hydrogen sensor based on a Fabry–Pérot Interferometer (FPI) consisting of a fiber-tip graphene–Au–Pd submicron film cantilever. The palladium (Pd) film on the cantilever surface is used as hydrogen-sensitive material to obtain high sensing sensitivity. Hydrogen sensing is realized by monitoring the resonant frequency shift of the FPI introduced by the interaction between Pd film and hydrogen molecules. The hydrogen sensor is proven for low-hydrogen-concentration detection with hydrogen concentrations in the range of 0–1000 ppm, and experimentally characterized by a highest sensitivity of 30.3 pm ppm⁻¹ in a low hydrogen concentration of 0–100 ppm, which is more than two orders higher than for previously reported FPI-based sensors. In real-time hydrogen monitoring, a rapid reaction time of 31.5 s was achieved. This work provides a compact all-optical solution for the safe detection of low hydrogen concentrations, which is an interesting alternative for trace hydrogen detection in the aerospace industry, energy production, and medical applications.

suffer from shortcomings like cross-sensitivity with interfering gases, high cost, low sensitivity, portability issues, *etc.*¹

Several optical-fiber-based sensors have recently been proposed for hydrogen monitoring, avoiding the potential explosion hazard of electrochemical hydrogen sensors.9-20 In 2019, Ma et al. proposed a fiber-optic Fabry-Pérot (F-P) hydrogen sensor based on graphene-palladium (Pd) film, where the graphene film was used as a surface to bear Pd to achieve significant deformation in FPI. Their experimental results showed that the F-P hydrogen sensor had a response time of 18 s and a limit of detection of 20 ppm.¹⁹ They also noticed that, in addition to amplifying mechanical changes through thin-film materials such as graphene, which can withstand large bending forces, mechanical structures such as cantilevers could also be used to magnify mechanical changes.¹⁹⁻²⁹ For example, a cantilever structure can transform a tiny change in mass or force into significant bending, which is especially suitable for small-molecule detection.^{30–37} As early as 2003, Baselt et al. first used a microelectromechanical (MEMS) cantilever for hydrogen sensing.³⁸ In 2007, Iannuzzi et al. designed a Pd-coated cantilever hydrogen sensor based on a fiber-top thin rectangular beam, which was fabricated out of the cleaved edge of a single-mode optical fiber.³⁹ More recently, Xiong et al. proposed a Fabry-Pérot Interferometer (FPI) hydrogen sensor formed from a polymer microcantilever deposited with a 120 nm thick Pd film.40 The

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[†] Electronic supplementary information (ESI) available. See DOI: https://doi.org/ 10.1039/d2lc01149b

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sensor exhibited a hydrogen sensitivity of ~2 nm/% in the hydrogen concentration range from 0% to 4.5% (V/V) and a response time of 13.5 s at 4% (V/V). Due to the evident deflection generated by the interaction of hydrogen and Pd, the mechanical microcantilever-based sensor has high sensitivity to hydrogen. More importantly, the optical measurement avoids potential explosion caused by electronic measurement. However, in some cases, such as in microbial biochemical reactions or disease monitoring, safe detection of hydrogen is required in a small space with narrow pipes, necessitating the use of a tiny hydrogen sensor with high sensitivity for ultra-low concentration or even trace hydrogen sensors capable of operating in small spaces and ultra-low hydrogen concentration ranges are particularly needed.

This work proposes a tiny FPI-based hydrogen sensor based on a fiber-tip graphene-Au-Pd submicron film cantilever for low-hydrogen-concentration detection. The fiber-optic Fabry-Pérot interferometer is formed from a short capillary with one end facet spliced with a single mode fiber (SMF), and the other end facet covered by graphene-Au-Pd composite film. The trampoline-shaped cantilever is etched on the composite film by a focused ion beam (FIB). The geometric features of the cantilever are analyzed with a Raman spectrometer, scanning electron microscopy (SEM), and atomic force microscope (AFM). The hydrogen sensing performances of the proposed sensor, including sensing sensitivity, response time, and repeatability are experimentally verified. The sensor has a high sensitivity of 30.3 pm ppm^{-1} in low hydrogen concentrations (0–100 ppm). At 800 ppm, the fastest response time is 31.5 s. These outstanding sensing features mean the proposed hydrogen sensor shows promise as a compact all-optical solution for the safe detection of low concentrations.

2. Experimental methods

2.1 Sensing principle

A diagram of the structure of the proposed hydrogen sensor is shown in Fig. 1(a). A short capillary glass tube is connected to an SMF, and the interface acts as one end face for the fiber-tip FPI. The other end of the capillary glass tube is covered by a graphene–Au–Pd submicron film with a rectangular cantilever. The fiber end face and the lower surface of the cantilever serve as two mirrors for the FPI, and the light reflected by these two mirrors creates an interference spectrum. The Pd coating on the sensor interacts with hydrogen molecules when it is exposed to hydrogen gas, causing the Pd lattice to expand. The interaction formula is:

$$xH_2 + 2Pd \leftrightarrow 2PdH_x \tag{1}$$

where *x* is the number of hydrogen atoms. Hydrogen molecules dissociate into elemental hydrogen and rapidly diffuse into the interior of the Pd membrane. The H_2 sorption process of the Pd membrane has the following steps: external mass transfer, surface adsorption, dissociation, diffusion, recombination and



Fig. 1 Schematic images of the sensor. (a) Schematic diagram of the proposed hydrogen sensor based on a graphene–Au–Pd cantilever. (b) Scanning electron microscopy (SEM) image of the cantilever surface; the inset figure illustrates the top view of the cantilever surface. (c) Side view of the sensor obtained by a microscope.

desorption.⁴³ In this interaction system, there are two phases: α -phase (solid solution of Pd and H) and β -phase (Pd hydride). Both phases exist in the adsorption process of H atoms. When the number of integrated H atoms exceeds the maximum solid solubility in the Pd layer, the absorption process undergoes a phase shift from α - to β -phase, resulting in a 10% volume expansion.45,47 Desorption occurs when the external hydrogen pressure is reduced, leaving only the β -phase. During the phase transition from α -phase to β -phase and back to α -phase, the Pd thin films exhibits hysteresis behavior as well as irreversible structural changes, posing serious stability challenges.^{47,51} It has been found that for a Pd film with a thickness of 5 nm, the hysteresis behavior disappears, which alleviate the problem of Pd film instability.⁵¹ The sorption process of Pd and hydrogen is reversible, so that the Pd film can return to its original state when it leaves the hydrogen atmosphere, as shown in Fig. 3(a and b). Sievert's law is applied to describe the equilibrium concentration of hydrogen atoms inside the Pd, denoted as C:⁴⁴⁻⁴⁶

$$C = K_{\rm H_2}(P_{\rm H_2})^n \sim \sqrt{(C_{\rm H_2})_{\rm external}}$$
(2)

where K_{H_2} is the Sievert constant, which was fitted by an Arrhenius-type relationship $(K_{\text{H}_2} \sim \exp(-\frac{E}{RT}))$, *n* equals 0.5 in the ideal situation, and C_{H_2} is the concentration of the external hydrogen gas.

Due to the Pd lattice expansion caused by this reaction, the top and lower surfaces of the cantilever experience different stresses, which results in the cantilever bending. We assume that the Young's modulus of the graphene–Au–Pd cantilever remains stable during the hydrogen adsorption process, so the bending deflection of the cantilever due to hydrogen adsorption can be expressed as:^{40,47}

$$Z = 3(\alpha_{\rm Pd} - \alpha_{\rm f}) \left(\frac{t_{\rm Pd} + t_{\rm f}}{t_{\rm f}^2 k}\right) CL^2$$
(3)

where *L* is the length of the cantilever, and t_{Pd} , t_f and α_{Pd} , α_f are the layer thicknesses and expansion coefficients,



Fig. 2 Characterization of the cantilever on the fiber tip. (a) SEM image of graphene film. (b) Raman spectrum of the multilayered graphene film. (c) and (d) The thickness profiles of Au film and Pd/Au film, respectively. The inset figures present the AFM image of glass-Au film and glass-Au/Pd film, respectively.



Fig. 3 (a) Schematic diagram of the sensing mechanism of a Pdcoated cantilever. (b) Reflection spectrum of the cantilever-type sensor in air.

respectively. The subscript f refers to the cantilever foundation, which consists of graphene film and Au film. C is the concentration of hydrogen atoms in the Pd film, depending on C_{H_2} as described in eqn (2). The quantity k is determined from the Young's moduli and thickness of the cantilever and Pd film.⁴⁷ According to the equation, the bending deflection (Z) of the cantilever is proportional to hydrogen concentration (*C*) and consistent with the change in cavity length (Δl) of the FPI. The Δl can be monitored by the change in dip wavelength ($\Delta \lambda$) of the FPI spectrum with the equation $\Delta \lambda / \lambda = \Delta l / l$.

2.2 Sensor fabrication and characterization

Fig. 1(b) and (c) present the top view of the cantilever and the side view of the fiber-top FPI, respectively. The fabrication process of the hydrogen sensor was divided into three steps: (1) formation of the F–P cavity over the fiber tip with graphene; (2) coating the fiber tip with Au and Pd for graphene–Au–Pd film; (3) fabrication of the cantilever on the graphene–Au–Pd film. The details are illustrated in Fig. S1 of the ESI† material. In the first step, one end facet of a 15 μ mlength capillary (O.D. 125 μ m, I.D. 75 μ m) was fused to an SMF by a commercial fusion splicer. On the other hand, a graphene sheet was transferred to the other end facet of the hollow-core fiber (HCF) by a wet transfer method, as mentioned in previous reports.^{18,40}

The multilayered graphene film was obtained from a graphene/Cu sample (SixCarbon Technology (Shenzhen)). A graphene film consisting of 6-8 layers on a copper film (50 µm thickness) was fabricated by chemical vapor deposition. Because single-layer graphene has a thickness of 0.34 nm, the thickness of 6-8 layers of graphene can be estimated to be 1.5 nm. In order to remove the Cu layer, the graphene facet of the graphene/Cu sample was put into an etching solution (0.075 g mL⁻¹ FeCl₃ solution). When the Cu layer had been removed, the FeCl₃ solution was carefully removed using an injection syringe before injecting deionized water. To remove the remaining ions on the graphene sheet, the procedure was repeated several times. Next, the tip of the fiber was directed toward the floating graphene sheet to create a fiber-tip FPI with the graphene film (G-FPI). Due to van der Waals force, the graphene film remained securely connected to the fiber-tip end facet while the remaining water of the suspended graphene film on HCF evaporated. The HCF end facet was thus securely bonded to the graphene layer. Due to its exceptional mechanical properties and ductility, graphene is the ideal material to be used as a bearing surface for cantilevers.48-50 Fig. 2(a) presents the SEM image of the graphene film suspended on the capillary end face, from which we can ensure the smooth and flat graphene film has been successfully transferred to the capillary surface. The graphene features were also characterized with a Raman spectrometer (WITec Alpha 300R), as shown in Fig. 2(b). The red curve is the Lorentzian fit of the Raman curve. According to the relative ratio of the G (1583 cm^{-1}) peak to to the 2D (2695 cm⁻¹) peak value, the graphene film was determined to be 6-8 layers, consistent with the reference number of layers given for commercial copper-based graphene sheets.

In the second step, a gold (Au) film was coated over the graphene film by placing G-FPI into the vacuum chamber of a magnetron sputtering coating device and spin sputtering for 2 hours. According to formula (2), as the thickness of the Au film increases, the deformation of the cantilever

decreases, lowering the sensitivity of the sensor. However, the gold film cannot be infinitely small because it also serves as a support film for the Pd film. The cantilever with 2 hours of coating was chosen for hydrogen sensing in order to allow the Au film to perform well in both supporting and bending functions simultaneously. An FPI based on the graphene-Au film (Au/G-FPI) was formed after this process. The Au film also acts as a sandwich material to improve the adhesion between two materials in addition to enhancing FPI contrast.¹⁸ The flatness and thickness of the Au film were characterized with an atomic force microscope (AFM), as shown in Fig. 2(a and b). The prepared Au film has good uniformity with a thickness of 396 nm. Since the thickness of commercial few-layered graphene is about 1.5 nm, the thickness of the Au/G composite film can be determined to be ~397.5 nm. Subsequently, a Pd film, as a hydrogen-sensitive layer, was coated on the surface of Au/G-FPI by the magnetron sputtering process. As shown in Fig. 2(c and d), the composite film is smooth, and the thickness of the obtained Pd film is about 5 nm through the thickness difference between the Pd/Au film and the Au film. Pd film can theoretically detect hydrogen with a concentration of up to 99.99%, and adsorb more than 900 times its volume at room temperature and pressure.14,10 Studies have shown that the volume expansion of the Pd film due to the adsorption of hydrogen leads to hysteresis of the subsequent hydrogen adsorption. But when the thickness of the Pd film is less than 5 nm, this phenomenon is negligible.⁵¹ Thus, the Pd-coated hydrogen sensor prepared in this paper overcomes the hysteresis of the hydrogen adsorption reaction and improves the sensing performance. Based on the data in Fig. 2(c), the Au/Pd composite film has a thickness of 401 nm. Taking the thickness of the graphene layers into account, the overall thickness of the cantilever is 402.5 nm.

Finally, the Pd/Au/G composite film was etched into a cantilever using a 0.3 nA electron beam launched by FIB technology. The surface view of the cantilever is illustrated in Fig. 1(b). The arm length and width of the cantilever are 60 μ m and 50 μ m, respectively. The reflection spectrum of the cantilever-type sensor in the air is presented in Fig. 3(b), demonstrating that the sensor has a free spectral range (FSR) of ~97.6 nm and an FWHM of ~26.48 nm.

2.3 Hydrogen measurement

The sensing capabilities of the FPI-based hydrogen sensor were assessed using an experimental setup consisting of the sensing part and gas control part, as illustrated in Fig. 4. The sensing part is on the left-hand side of the sensor (inside the red dashed box), consisting of path 1 and path 2. Path 1 is used for sensitivity assessment, where white light emitted from a broad-spectrum white light source (BBS) passes through the circulator to the sensor, then the light reflected from the sensor is output from the other end of the circulator and received by the spectrum analyzer (OSA, Yokogawa, AQ6317C). Path 2 is set to analyze the response time of the



Fig. 4 Experimental setup. Experimental setup for characterizing the optical spectrum of the sensor, sensitivity response, and time response to hydrogen. Paths 1 and 2 are used to measure the optical spectrum and time response characteristics of the sensor, respectively. The right-hand part of the sensor is the hydrogen concentration control setup. The lower figure in the green box illustrates the reversible reaction of Pd film and hydrogen molecules.

sensor: a single wavelength of light generated by a tunable laser (Agilent 81940A) passes through the circulator to the sensor. The light reflected by the sensor returns and propagates from the other end of the circulator. The output light is monitored by a photodetector (Newfocus 1544-B) and converted into an electrical signal, which is finally recorded by an oscilloscope (OSC) in the form of a voltage value. The right-hand side of the sensor is the hydrogen concentration control part (inside the blue dashed box): the hydrogen produced by the hydrogen cylinder (0.2% by volume) is mixed with pure nitrogen through a T-shaped three-way plastic tube. Two gas flow meters (Sevenstar-D07-1 and Sevenstar-D07-2) are applied to precisely control the hydrogen concentration in the mixed gas through a computer program with a control error of less than 1%. The D07-1 with a range of 0-500 standard cubic centimeters per minute (SCCM) is used to control the nitrogen flow, and the D07-2 with a range of 0-30 SCCM is used to control the hydrogen flow. Different hydrogen concentrations in the range from 0 to 1000 ppm can be produced with an error of less than 5% by adjusting the volume ratio of the mixed gas. In the measurement, the sensor is placed in a miniature plastic tube with a diameter of about 5 mm. The hydrogen concentration in the plastic tube is controlled from 0 to 1000 ppm (0.1%) with an increment of 100 ppm (0.01%). Each measurement lasted for 5 minutes to confirm that adsorption equilibrium was reached. The lower figure in the green box illustrates the reversible reaction of Pd film and hydrogen molecules.

3. Hydrogen sensing properties

3.1 Frequency response

Fig. 5(a) shows the reflection spectra from 1550 nm to 1600 nm of the sensor under different hydrogen concentrations.

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The dip wavelength shift $(\Delta \lambda)$ of each hydrogen concentration was obtained by averaging three measurement. As the hydrogen concentration increases, the dip wavelength gradually blueshifts because the Pd film adsorbs hydrogen molecules and leads to length changes of the FPI cavity. The wavelength of the dip near 1577 nm shifts by 5.60 nm when the hydrogen is in the range 0 to 1000 ppm. The adsorption of hydrogen by the Pd membrane can be analyzed by Langmuir solid adsorption theory.^{52,53} Therefore, the hydrogen concentration and dip wavelength shift show an S-shaped curve relationship in the adsorption equilibrium state. Fig. 5(b) shows the Boltzmann fitting of the dip wavelength shifts under different hydrogen concentrations, with a fitting coefficient of R^2 = 0.9832. It is noteworthy that an H_2 concentration of 100 ppm caused a significant wavelength shift of 3.03 nm, which translates to an H₂ sensitivity of 30.3 pm ppm⁻¹. The sensitivity of this sensor is more than two orders of magnitude higher than that of previously reported FPI-based hydrogen sensors.^{19,40} According to eqn (2), for the same hydrogen concentration, a thinner and longer cantilever and thicker Pd films potentially result in a higher cantilever deflection, which in turn increases the sensing sensitivity. Therefore, the increased sensitivity could be attributed to the additional trampoline-shaped cantilever of the FPI, which has a relatively thinner thickness and longer length.



The hydrogen response repeatability of the sensor was also experimentally investigated in this work. During the experiment, the hydrogen concentration was cycled between 0 and 1000 ppm three times. The reflectance spectra of the sensor at various hydrogen concentrations were measured and the corresponding dip wavelength values were recorded. Each measurement lasted 3 minutes to ensure that the Pd film adsorbed hydrogen to an equilibrium state. Fig. 6(a) shows the dip wavelength shift of the three cycles arranged side by side. The maximum dip wavelength shifts in the three cycles are 5.42 nm, 5.60 nm, and 4.88 nm, respectively. Through the horizontal comparison, it can be found that the dip wavelength values are relatively stable under the same hydrogen concentration, both in the increasing process and in the decreasing process. To visually see the similarity of the three sets of cyclic data, the data are stacked under the same coordinates, as shown in Fig. 6(b). The dip wavelength shift curves of the three cycles overlap, indicating that the sensor has superior repeatability for hydrogen sensing. The slight differences in the dip wavelength shift for the three cycles may be due to the uneven distribution of hydrogen in the plastic tube and the different initial states of the cantilever.

3.2 Response time

To demonstrate the performance of hydrogen sensing, the reaction time of the sensor was examined at various hydrogen concentrations. In the experiment, the original reflectance



Fig. 5 Spectral response of the sensor to the hydrogen concentration. (a) The response spectra of the sensor under varying hydrogen concentrations. (b) The relationship between dip wavelength shift and hydrogen concentration. The red line shows the Boltzmann fitting curve of the experimental data.

Fig. 6 The reproducibility of the sensor for three detections. The reproducibility data of the sensor is monitored at hydrogen concentrations between 0 and 1000 ppm for three cycles. The three sets of cycle data are arranged beside each other (a) and overlapping each other (b).

spectrum of the sensor is selected to scan at the maximum slope of the resonant dip, which is ~1581.5 nm at full width at half maxima (FWHM) of the resonant peak. The experimental test consists of the purge phase of pure nitrogen and the test phase under different hydrogen concentrations. These two phases are carried out alternately. In the test phase, the hydrogen concentrations are set to be 200 ppm, 400 ppm, 600 ppm, 800 ppm, and 1000 ppm. Fig. 7(a) presents the timedomain spectrum of the sensor in the experimental test. The voltage value increases quickly in each test phase and tends to be stable. When the experiment turns to the purge phase, the voltage returns to a position near its initial voltage value. According to solid adsorption theory, the time-response curve of the adsorption process satisfies Boltzmann fitting, and the response time is defined as 90% of the total time for the curve to reach a steady state. Therefore, the response times of the sensor in the hydrogen concentrations range of 200-1000 ppm were 41 s (@200 ppm), 39.5 s (@400 ppm), 35.8 s (@600 ppm), 31.5 s (@800 ppm), 32.2 s (@1000 ppm).

Fig. 7(d) exhibits the relationship between the response time of the sensor and the hydrogen concentration. The concentration of hydrogen influences the speed of the hydrogen sorption processes in the Pd membrane, which influences the response time of the sensor.⁴³ As illustrated in the figure, the diffusion rate increases with the proportion of Pd surface sites occupied by hydrogen atoms as the external hydrogen



Fig. 7 The response time evaluation of the sensor. (a) Response time of the sensor with various hydrogen concentrations at 1581.5 nm wavelength. (b) and (c) Enlarged view of the response curve at hydrogen concentrations of 800 ppm and 1000 ppm, respectively. (d) Relationship between response time and hydrogen concentration.

concentration increases, resulting in a shorter response time. In this case, the adsorption rate is significantly higher than the desorption rate in the initial stage of the adsorption reaction.³⁹ However, the response time at a hydrogen concentration of 1000 ppm is 32.2 s, which is longer than that at a concentration of 800 ppm, with the enlarged view of the response curves illustrated in Fig. 7(b) and (c). As the hydrogen concentration approaches 800 ppm, the hydrogen on the Pd film surface approaches saturation, and the diffusion rate of hydrogen atoms to the interior of the Pd film becomes steady. Hence, the diffusion rate is fairly steady at 800 ppm, so the response time increases slightly because more hydrogen atoms need to diffuse into the inner Pd layer.^{19,40} In addition, due to the tight coupling between hydrogen and Pd film, the escape rate of hydrogen molecules slows down, consequently leading to a longer recovery time of the sensor than the corresponding response time. Therefore, the fastest response time of the sensor is determined to be 31.5 s.

3.3 Repeatability between sensors

The reproducibility of the hydrogen sensor was investigated by comparing the structural and average sensitivities of three samples, as illustrated in Fig. 8. These samples, denoted as Sample 1 (the primary focus of this study), Sample 2, and Sample 3, were fabricated using identical processing parameters. The HCF lengths for Sample 1, Sample 2, and Sample 3 spliced to an SMF end facet were approximately 15 µm, 19.7 µm, and 23.5 µm, respectively. Initially, the end facets of all three samples were covered with a multilayered graphene film. Subsequently, they were sequentially coated with a 400 nm thick layer of Au film and a 5 nm thick layer of Pd film. Fig. 8(a-c) displays the SEM images of Sample 1, Sample 2, and Sample 3. The geometric structures of the prepared samples exhibited remarkable similarity, indicating the potential for mass production. Additionally, their hydrogen sensing performance was tested within the range of 0-1000 ppm, as depicted in Fig. 8(d). The average sensitivities



Fig. 8 The reproducibility of the sensor. The SEM images of (a) sample 1, (b) sample 2 and (c) sample 3 and the wavelength shifts of the three samples. The fabrication parameters of the three samples were the same. (d) The dip wavelength shift of these samples in different hydrogen concentrations.

within this hydrogen concentration range were found to be 5.60 pm ppm⁻¹, 4.32 pm ppm⁻¹, and 5.70 pm ppm⁻¹ for Sample 1, Sample 2, and Sample 3, respectively. The striking resemblance among these samples validates the repeatability and reliability of the proposed method outlined in this paper.

4. Conclusions

In conclusion, we proposed a novel fiber-top FPI-based hydrogen sensor with a graphene-Au-Pd cantilever. The cantilever, which was formed by etching the graphene-Au-Pd composite submicron film by the FIB technique, was located on the end face of a capillary in a semi-suspended state to construct the fiber-top FPI. The Pd film with a thickness of 5 nm was utilized as hydrogen-sensitive material for the sensor. The hydrogen sensing performances of the sensor were experimentally verified by exposing it to a hydrogen environment with a low hydrogen concentration of 0-1000 ppm (0-0.1%). The experimental results showed that the sensor exhibits a high sensitivity of 30.3 pm ppm⁻¹@1577 nm to low hydrogen concentration. The fiber-top hydrogen sensor with a graphene-Au-Pd cantilever proposed in this study enables it to work in narrow pipelines, storage tanks, electronic circuits, and other areas with limited space, providing a compact all-optical solution for the safe detection of a low concentration of hydrogen. Furthermore, a sensor based on a cantilever is widely suitable for other small-molecule gas, chemical, and biological detection by using other sensitive layered materials.

Author contributions

Junlan Zhong: conceptualization, methodology, writing – original draft preparation; Shengzhen Lu: conceptualization, methodology, writing – original draft preparation; Shen Liu: conceptualization, methodology, funding acquisition; Peijing Chen: writing – reviewing and editing; Junxian Luo: investigation; Yanping Chen: visualization; Guiqing Hong: resources; Xizhen Xu: funding acquisition. Junle Qu: writing – reviewing and editing; Liwei Liu: writing – reviewing and editing; Ying Wang: funding acquisition; Yiping Wang: project administration, supervision.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (NSFC) (62175165, 61905165); the Guangdong Basic and Applied Basic Research Foundation (2021A1515011834, 2019A050510047); and the Shenzhen Science and Technology Program (RCBS20200714114922296, JCYJ20210324120403009, JCYJ20220818095615034).

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