A novel mechano-optical sensor based on read-out with a Si_3N_4 grated waveguide

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Microcantilever-based sensors can be used to detect molecular absorption of, for example, hydrogen gas, which causes changes in the surface stress, leading to deflection of the cantilever. Such a deflection can be determined by means of optical beam deflection, capacitance-, or piezo-resistance based readout. We have recently proposed a compact integrated mechano-optical sensor using a novel and highly sensitive integrated read-out scheme to detect small deflections of a cantilever in close proximity to a grated waveguide (GWG) structure. Here we present the integrated optical read-out of stress-induced micro-bridge deflections due to hydrogen gas absorption by a Pd receptor layer on top of the micro-bridge.

Introduction

A sensor is a device that can recognize the presence of a specific stimulus and translate it into a measurable signal [1]. Microcantilever-based sensors, which have effectively been exploited for biological, chemical, and gas sensing applications, can be operated in either dynamic mode by monitoring the resonant frequency of the cantilever (CL), or static mode by measuring its stress-induced deflection, as the target binds to the functionalized surface of the CL [2]. The deflection of the CL can be determined by means of bulky deflection of an optical beam [3] or electrical, i.e., capacitive, piezo-resistive, or piezoelectric readouts [4-6]. Alternatively, fully integrated optical read-out with a CL waveguide was firstly presented in 2006 by Zinoviev *et al.* [7] and in the following three years by other groups [8-10]. In 2008, we proposed a novel integrated optical read-out of singly-clamped CL (sCL) bending with a grated-waveguide (GWG) optical cavity and presented preliminary simulation results [11]. Recently, such integrated mechano-optical GWG-sCL devices have been fabricated and demonstrated as a proof of concept of the read-out [12].

Design aspects

In this study, we aim at applying the proposed integrated mechano-optical readout to hydrogen gas sensing. For this purpose, a 30-nm-thick palladium receptor layer was sputtered onto the entire surface of the SiO_2 CL. At room temperature and atmospheric pressure, palladium can absorb up to 900 times its own volume of hydrogen [13]. Absorption of H_2 by Pd causes the CL, suspended above the GWG, to curl down [3-12], which narrows the GWG-CL gap, *g*, and leads to a stronger interaction between the CL and the GWG evanescent modal field, which results in a red-shift of the transmission spectrum.

Functionalizing the SiO_2 CL by depositing the absorptive palladium film onto it causes an initial bending of the bi-layer CL due to difference in their residual stresses [12]. In the fabrication batch presented in Ref. [12], an oxygen-plasma treatment was strategically applied as a means to reduce such an initial bending of the bi-layer sCL. As a side effect, the palladium film was oxidized and no longer able to bind H_2. Therefore, a solution to achieve a low initial bending of the CL without deactivating the functionality of the palladium film is required. One of our proposed solutions consisted of using devices with a doubly-clamped CL –a so-called bridge– in addition to the sCLs as mentioned in Ref. [12].

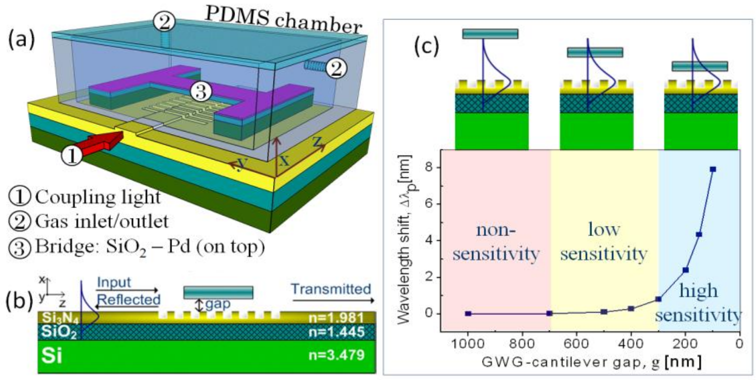

Fig. 1. (a) 3D schematic of the structure with a PDMS chamber serving as a reaction environment for H_2 sensing, (b) cross-section of the GWG-CL device, and (c) simulated resonant wavelength shift for various gap sizes, illustrating three operating regions of the sensor.

A three-dimensional (3D) schematic of the structure and the cross-section of the GWG-micro-bridge device are shown in Figs. 1a and 1b. All relevant device dimensions remain the same as in Ref. [12], except that here we choose an aimed gap of g_o = 200 nm and a bridge length of L_b = 65 µm. A polydimethylsiloxane (PDMS) chamber was placed on top of the device and connected to gas bottles with pure N_2 and a 1% H_2-N_2 mixture through mass-flow controllers. The optical performance of the integrated device was monitored using a tunable laser source (Agilent 8164B) with a resolution of 1 pm and an InGaAs photo-detector.

Response of the sensor with different gaps was simulated using the bi-directional eigenmode propagation method, as shown in Fig. 1c [11]. The results indicate roughly three sensitivity regions of the sensor, depending on the overlap of the CL with the evanescent tail of the GWG modes.

Finite-element simulations of the CLs were carried out using the INTELLISUITE software package [17], as shown in Fig. 2a (only the bridge structure is shown here). The initial bending of the fabricated sCL and bridge was characterized using a white-light interferometer. Figure 2b shows a 3D image of the fabricated bridge, as recorded with a white-light interferometer, indicating an initial bending (upwards, i.e., away from the GWG structure) of approximately 500 nm. Analytically calculated using the Timoshenko formulas [14-16] (not presented here), numerically simulated, and experimentally measured values of the initial deflections are in good agreement and summarized in Table 1. The Table also shows the resulting gap, $g = g_0 + \delta_0$, of the GWG-sCL/bridge devices. The GWG-sCL device is not suitable for H_2 sensing, because the gap g ~ 3155 nm is in the insensitive region of the sensor. On the contrary, the GWG-bridge device is able to detect H_2, even though the gap g ~ 700 nm is in the low-sensitivity region of the sensor, as predicted in Fig. 1c. This initial bending leads to a lower sensitivity at low H_2 concentrations.

Experimental

Prior to supplying H_2 gas to the measurement chamber, N_2 gas was flushed in during 15 min with a flow rate of 0.5 sccm and optical transmission curves were captured

Table 2. Initial bending δ_0 of the CLs and the final fabricated gap $g = g_0 + \delta_0$, and sensitivity for thermal drift $\Delta\delta/\Delta T$

	sCL	Bridge
Length (µm)	30	65
Calculated δ_0 (nm)	2977	473
Simulated δ_0 (nm)	3196	~510
Measured δ_0 (nm)	~2955	~500
Fabricated gap g (nm)	~3155	~700
Calculated $\Delta\,\delta/\Delta T$ (nm/K)	~2.5	~0.4

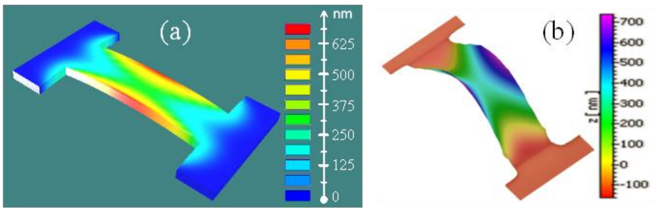

Fig. 2. Initial bending of the bridge due to differences in residual stress of the films: (a) numerical simulation using INTELISUITE software package, (b) experimental result attained by a white-light interferometer, showing an initial up-bending of ~500 nm at the center of the micro-bridge

repeatedly every minute. The results showed a stable and reproducible resonant peak at λ_p = 1496.631±0.001 nm (see Fig. 3a, curve at t = 0), indicating that such a flow rate did not cause any side effects or mechano-optical vibrations. Noise was removed from the spectrum using low-pass filtering in the Fourier domain, enabling accurate and efficient determination of changes in $\Delta\lambda_p = \lambda_p(t) - \lambda_p(t_o)$.

Next we supplied the H_2(1%)-N_2 mixture at a flow rate of 0.5 sccm for a longer period of time, during which the transmission spectrum was monitored (see Fig. 3a). The shift $\Delta\lambda_p$ depends almost linearly on time (Fig. 3b, left-hand side), which can be explained partly by noting that the effect of the initially rapid change of the gap size, g, is compensated by lower values of $\partial\lambda_p / \partial g$ at larger gap size. After 3.5 hours the flow of the H_2 (1%)-N_2 mixture was switched off and replaced again by a pure N_2 flow, leading to desorption. Figure 3b (right-hand side) shows the resulting peak shifts during a four-hour period. It can be concluded that the desorption takes place at a much lower rate of ~50% than the absorption process, and full desorption is not achieved during the monitoring period of time.

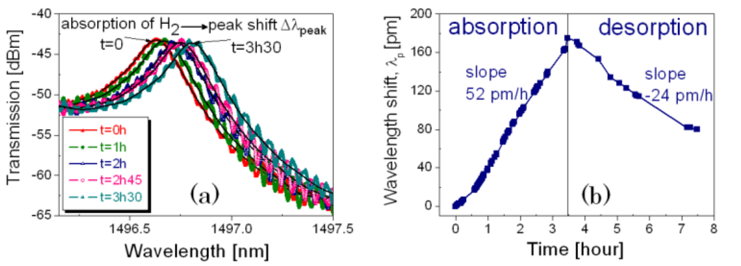

Fig. 3. (a) Transmission curves of the device in response to the absorption (filtered and unfiltered curves) and (b) the amount of wavelength shift $\Delta\lambda_p$ versus the reaction time: absorption (left-hand side) and desorption (right-hand side).

In practice, operation of the sensor is also affected by environmental changes due to the fluctuations in temperature, ΔT. The difference in the thermal expansion coefficients between Pd and SiO_2 causes a deflection change of ~ 2.5 nm/K for the sCL and ~ 0.4 nm/K for the bridge, as estimated theoretically. In addition, a temperature change also leads to a spectral shift of the grated-waveguide read-out. The resonant wavelength peak due to the temperature variation is measured, as shown in Fig. 4. The result shows a linear relationship $\lambda_p(T)$ with a slope $\Delta\lambda_p/\Delta T$ = 16 pm/K.

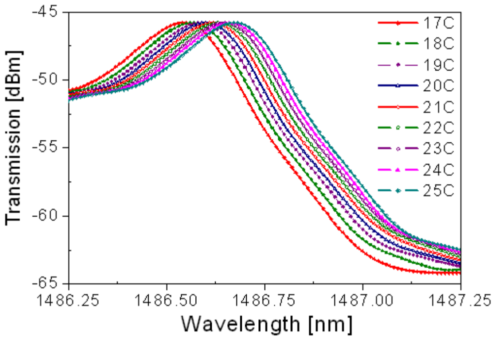

Fig. 4. Temperature dependence of the integrated optical readout; the change of resonant wavelength shift is 16 pm/K.

Conclusions

We have demonstrated H_2 sensing with a novel and compact integrated optical read-out scheme as a proof of concept for a mechano-optical sensor. It was found that the error in the peak shift, owing to noise and thermal fluctuations in the temperature-stabilized set-up, is around 1 pm. Then, using that $\Delta\lambda_p/\Delta g$ = 0.1, 0.8, and 30 pm/nm, at a gap of g = 700, 500, and 200 nm, respectively (according to the theoretical curve in Fig. 1c), the error in detection of the gap is given by 10 nm, 1.25 nm, and 33 pm for the aforementioned gap sizes, respectively. This new sensor type possesses a great potential as an element of a sensitive, on-chip multi-sensing system, provided that the gap between the GWG and the micro-cantilever, i.e., sCL and bridge, can be well controlled during fabrication.

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