Enhancement of real-time resonance tracking in electro-thermally actuated cantilever sensor with optimized phase characteristic

A Setiono\textsuperscript{1,2,*}, J Xu\textsuperscript{1}, M Fahrbach\textsuperscript{1}, M Bertke\textsuperscript{1}, W Ombati Nyang’au\textsuperscript{1,3}, H S Wasisto\textsuperscript{1} and E Peiner\textsuperscript{1}

\textsuperscript{1}Institute of Semiconductor Technology (IHT) and Laboratory for Emerging Nanometrology (LENA), Technische Universität Braunschweig, Hans-Sommer-Straße 66, D-38106 Braunschweig, Germany
\textsuperscript{2}Research Centre for Physics, Indonesia Institute of Sciences (LIPI), Kawasan Puspitek Serpong, 15314 Tangerang Selatan, Indonesia
\textsuperscript{3}Department of Metrology, Kenya Bureau of Standards (KEBS), Nairobi 00200, Kenya

* Corresponding e-mail: a.setiono@tu-braunschweig.de

Abstract. Non-ideal phase responses on electro-thermally actuated piezoresistive cantilever sensors have led the phase-locked loop (PLL) systems into difficulties for real-time sensing applications. These outcomes are caused by thermal-parasitic coupling from the actuating part to the sensing part. Minimizing or eliminating parasitic effects is necessary to obtain an optimized phase response. To realize this, we adjusted the voltage supply of the sensing part, which is in form of a full Wheatstone bridge (WB). By increasing the WB supply voltage \( V_{WB} \), the phase response can be enhanced. Alternatively, a reference signal that differentially eliminates the parasitic parameter from the sensor output was employed. To investigate the resulting optimized phase response under real-time measurement conditions, two different microcantilevers were connected to an MFLI lock-in amplifier + PLL system (Zurich Instruments). Measurement results exhibited a good sensor performance under varying humidity and temperature conditions.

1. Introduction

Microcantilevers are among the most simplified and widely used spring-mass structures in the field of Micro-Electro-Mechanical System (MEMS)-based sensors. Cantilever sensors can work in both static and dynamic modes. In dynamic mode, a cantilever sensor extracts its resonant frequency, which is indicated by a characteristic peak in the amplitude/magnitude spectrum of the sensor output. The measured sensing targets (e.g., airborne nanoparticles, toxic gases, and humidity) can be detected by monitoring the resonant-frequency shift [1–8]. Nevertheless, MEMS cantilever sensors require an effective read-out system, especially for real-time measurement purposes. By measuring in real-time, data is speedily collected to evaluate the measuring parameters immediately. In connection with resonant sensors, phase-locked loop (PLL)-based systems are broadly used to enable a continuous resonant-frequency tracking in real-time/online [9–11]. Here, an optimized phase response showing a monotonic frequency dependence at resonance becomes an essential characteristic to expedite resonance locking.
A monotonic phase response of a piezoresistive cantilever sensor is depicted in figure 1(a), showing an unambiguous phase value at resonance, i.e., the frequency with the highest amplitude. Conversely, a non-ideal phase response (figure 1(b)) shows a reversing shape at resonance that leads to difficulties in locking the resonant frequency during online measurements. A MEMS cantilever sensor with an electro-thermal actuating element normally generates such a reversing phase response at its resonance. Low thermal-mechanical coupling and parasitic direct thermal coupling [12] are inhibitive to an ideal phase response. By implementing a reference signal that is subtracted from the sensor output, the phase response can be optimized. Another method to reduce thermal-parasitic coupling is a supply-voltage adjustment of the sensing part that leads to an enhancement of the mechanical phase shift in resonance. In this work, we combine both approaches for online measurements using piezoresistive cantilevers connected to an MFLI lock-in amplifier + PLL system (Zurich Instrument). Finally, continuous resonance-tracking experiments are performed under varying environmental parameters, such as temperature and humidity.

Figure 1. Measured amplitude- (black cross symbols) and phase- (red plus signs) responses of a piezoresistive cantilever excited by (a) an external piezoactuator, and (b) on-chip electro-thermal actuation.

2. Electro-thermally Actuated MEMS Cantilever Sensor

The electro-thermally piezoresistive cantilever sensors of this study (figure 2(a)) comprise two main parts, i.e., mechanical actuation and electrical sensing, which both are realized in the form of diffused p-type silicon resistors (figure 2(b)). Mechanical actuation is obtained by applying an AC voltage \( V_{ac} \cos(\omega t) \) superimposed on a DC voltage \( V_{dc} \) to a heating resistor (HR), which is located laterally at the cantilever clamped-end. The resulting power loss (dissipation) \( P \) of [4, 13]:

\[
P = \frac{V_{dc}^2}{R} + \frac{V_{ac}^2}{R} + \frac{2V_{dc}V_{ac}}{R} \cos(\omega t) + \frac{V_{ac}^2}{R} \cos(2\omega t)
\]  

where \( R \) is resistance of the HR, \( V_{dc} \) and \( V_{ac} \) are the DC and AC voltage amplitudes, respectively, and \( \omega \) is the angular excitation frequency, leads to Joule heating yielding a lateral temperature gradient around the HR.
This temperature distribution induces a strain gradient, which finally results in a cantilever bending in lateral direction (in-plane mode). The DC component is necessary to have a large excitation amplitude at the excitation frequency $\omega$ (third term in Eq. (1)). The response to cantilever bending, i.e., mechanical actuation is sensed by four piezoresistors configured in a U-shape full Wheatstone bridge (WB), where this design has been adapted to the strain distribution at the cantilever top surface during lateral bending. The sensing piezoresistors near the HR, i.e., $R_1$ and $R_2$, are more exposed to direct thermal heating than $R_3$ and $R_4$, as shown by finite element modelling (FEM, cf. figure 2(c)) using COMSOL Multiphysics. This parasitic thermal crosstalk, which is expected to result in a non-ideal phase response around resonance, can be described by:

$$V_{HR}(T) = \lambda(T) \times i_{HR}(T)$$

where $V_{HR}$, $\lambda$, $i_{HR}$ and $T$ are a parasitic voltage source coupled to the WB output, the coupling factor, the HR current amplitude and the temperature, respectively.

3. Experimental Setup

A reversing-phase characteristic in electro-thermal piezoresistive cantilevers is caused by thermal-parasitic crosstalk to the sensing part. In principle, removing these parasitic coupling can be carried out by cancellation or minimization of the parasitic effects at the resonator output. In this work, two methods based on adjustment of $V_{WB}$ on the sensing part and subtraction of a reference signal are employed and combined to obtain a Lorentzian amplitude shape and a monotonic phase response. In the first approach, the $V_{WB}$ adjustment is expected to cause a higher current and thus Joule heating in the WB, which consequently reduces the temperature gradient between the HR and the WB and thus the thermal crosstalk.

For the second method represented by the circuit in figure 3, a subtraction of a reference signal is performed by activating the switches $SW_1$, $SW_2$ and $SW_3$. To be more specific, amplitude and phase characteristics of a reference signal are differentially subtracted from the outputs of the electro-thermal piezoresistive cantilever sensor. Differential subtraction is performed by using both the inverting and non-inverting input terminals of a differential amplifier, which provides a resultant output voltage (OUT). The inputs of the amplifier are connected to the WB output signal $V_1$ of the cantilever and the reference output signal $V_2$. A circuit was designed and fabricated to provide a controlling mechanism for the reference amplitude and phase through $VR_1$ and $VR_2$. This circuit is intended to generate and provide a suitable characteristic reference signal, which can then be subtracted from cantilever signal. Finally, an MFLI lock-in amplifier and PLL system is operated to perform a continuous resonant
frequency tracking using the optimized phase shift. Two cantilever sensors are investigated, one ($C_{N1}$) under relative humidity (RH) changing in a climate chamber and the other ($C_{N2}$) under temperature changing by exposition to sunlight.

![Figure 3. Setup for phase characteristic optimization of an electro-thermal piezoresistive cantilever by subtraction of a reference signal.](image)

4. Result and Discussion

Figure 4(a) and 4(b) depict the amplitude and phase characteristics about resonance of the electro-thermal piezoresistive cantilever sensor at $V_{WB} = 2$ V and $V_{WB} = 4$ V, respectively. By increasing $V_{WB}$ to 4 V, the phase-shift range can be enhanced, but still exhibits a reversing behavior at resonance as illustrated in figure 4(b). Then, at $V_{WB} = 4$ V a reference signal (full line) is implemented and subsequently subtracted from the sensor output (cross and plus-sign symbols, figure 4(c)). As depicted in figure 4(d), the differential output yields a nearly Lorentzian amplitude shape and a monotonic phase shift.
Figure 4. (a) Amplitude and (b) phase responses of electro-thermal piezoresistive cantilever sensor at $V_{WB} = 2V$ and $V_{WB} = 4V$. (c) Employment of a reference signal to be subtracted from the cantilever sensor output, which (d) yields a monotonic phase shift range of $\sim 112^\circ$ at $V_{WB} = 4V$.

The reference-signal subtraction method was then investigated to prove its ability for locking the resonant frequency at the resonance phase efficiently. For this, the MFLI lock-in amplifier + PLL system was set to perform resonant-frequency tracking by referring to the resonance phase as the set point. Two microcantilever sensors with a rectangular mass spring of $l \times w \times h = 1000 \mu m \times 170 \mu m \times 12 \mu m$ were prepared as a bare silicon cantilever ($C_{N2}$) or, additionally, carry on its top surface a ZnO-nanorod array covered by self-assembled monolayers of chitosan ($C_{N1}$) [14]. Resonance characteristics are revealed by frequency sweeping using the MFLI lock-in amplifier. In figure 5(a) we find a good qualitative correlation of $\Delta f_R$ of $C_{N1}$ with RH set in a climate chamber (Weiss SB22/160/40; www. Bomatec.ch). Frequency shifts ($\Delta f_R$) show a high responsivity during RH increase in range of 40% to 50%, revealing that the combination of ZnO nanorods and chitosan is effective for collecting water molecules from air. Conversely, at the reversed condition, i.e., from 50% to 40%, frequency shifts ($\Delta f_R$) show a lower responsivity during change of RH. A slower evaporation rate of water molecules is expected as an inhibitive factor to the sensor response in this case.

Likewise, as shown in figure 5(b), $C_{N2}$ shows a good response to temperature changes compared with that measured by a thermometer. Frequency shifts ($\Delta f_R$) demonstrate a high responsivity during both increment and decrement of temperature. The temperature coefficient of the Young’s modulus and the thermal expansion coefficient are the intrinsic parameters of silicon that contribute most to its fast and reversible temperature response. It is different to the adsorbed-mass-based detection, e.g., of humidity, in which functionalization layers can lead to retarded removal of adsorbates from the cantilever beam.
Figure 5. (a) Resonant frequency shift of $C_{N1}$ (black line) under changing relative humidity (RH) in a climate chamber (red solid circle line). (b) Resonant frequency shift of $C_{N2}$ (black line) being exposed to changing sunlight under normal ambient conditions. The reading of a room thermometer (red solid square line) is shown for reference.

5. Conclusion

Optimized phase characteristics of electro-thermal piezoresistive cantilever sensors have been successfully achieved by subtracting a reference signal combined with the adjustment of the supply voltage of the Wheatstone bridge. The optimized phase response, introduced on MFLI lock-in amplifier + PLL system, exhibited enhanced performance of resonance tracking under various relative humidity and temperature conditions. Further work is necessary to develop an automatic adjustment of optimized phase shift and to implement it to a handheld system for resonant frequency tracking.

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