



Modelling and model verification of an autonomous threshold sensor for humidity measurements

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Received: 12 July 2019 – Revised: 23 October 2019 – Accepted: 29 October 2019 – Published: 6 January 2020

Abstract. Autonomous sensors that receive their energy from an energy harvester or directly from the environment have the potential to save energy for applications in numerous sectors. For humidity sensing, the swelling behaviour of a water vapour-sensitive hydrogel is used. To trigger an electrical contact the mechanical energy is taken from the hydrogel swelling by the bimorph effect. As long as a defined threshold is not reached, the electrical microcontact remains open. By passing the threshold value, a switching will be triggered causing the closure of the contact. This sensor principle does not need any electrical power supply because the switching power is provided directly by the surrounding humidity as quantity to be measured. For the description of the deflection versus the hydrogel pattern of such a sensor, a model was developed by means of the beam theory. Goal of the model was to derive design guidelines for the dimensioning of the sensors bending plate and the patterned hydrogel layer. Experiments then should show the applicability of the model approaches. The deflection of the bending plate depends on the ratio between the lengths of the uncoated and the coated part of the bending plate where the maximum occurs at a ratio of ca. 0.5. The swelling behaviour of the hydrogel shows a high sensitivity with regard to slight changes in relative humidity. This can be used for humidity threshold sensors that open and close microcontacts with respect to very small changes in relative humidity. To avoid voltage peaks and arcs during the switching process that could arise and destroy the microcontact, a bistable characteristic with hysteresis is needed. Experiments demonstrate the feasibility of this concept and are in good agreement with the modelling results.

1 Motivation

The recent progress in industrial production, building automation, automobile technology and many other fields leads to an increasing demand on sensors and sensor systems that combine data acquisition and signal processing. Such sensor systems have achieved above-average growth of more than 6 % per year (AMA, 2018) in the sensor and measurement technology industry in recent decades. Temperature and humidity are the most important measured quantities. However, in process control 70 % of all sensors are used as threshold switches and in building monitoring more than 90 %. In Bellmann et al. (2015), a novel approach for a non-powered humidity threshold switch based on the BIZEPS (binary zero-power sensor) principle was proposed (see also Frank et al., 2012; Rangelow et al., 2009; Rittersma, 2002). With this principle, the energy is taken directly from the measured

variable. In this work, a humidity threshold sensor switch is considered, where the moisture-dependent swelling of a hydrogel, which is part of a bimorph bending plate, is utilized. The switching hysteresis required to achieve an abrupt closing and opening of the contacts can be realized by applying a pre-deflection as well as an axial compression force. To prove this concept, in this work here a simple macro device is considered where both the pre-stress and the pre-deflection are applied by a screw acting axially on an elastically suspended bending beam coated with a humidity-sensitive hydrogel layer.

2 Setup and working principle

Figure 1 shows the general setup and working principle of MEMS-based moisture threshold switches (Huang et al., 2015; Dai et al., 2013). The silicon-based bending plate with

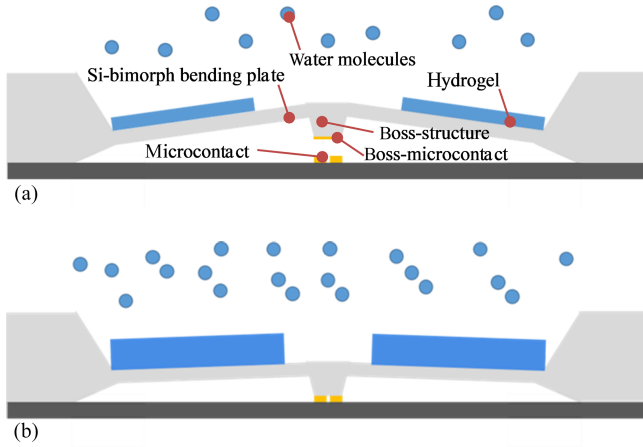


Figure 1. Humidity threshold sensor switch, consisting of a bi-morph bending plate with boss structure, a patterned hydrogel layer and microcontacts, (a) open, (b) closed.

a thickness of ca. 2×10^{-5} m is located in the middle of a silicon die of ca. 5×10^{-4} m thickness. In the middle, the thin plate comprises a thicker part – the so-called boss structure – that carries one part of the contact pair to be closed or opened. It ensures that the microcontact remains level and flat even if the bending plate is deflected. The humidity-dependent swelling of the hydrogel-coated silicon plate deflects the rigid centre of the bending plate. The water vapour uptake and, hence, the swelling state depend on the humidity of the surrounding air. When swelling, the hydrogel performs mechanical work and, thus, deflects the bending plate mechanically. That means that the energy is supplied by the environment and provides the opportunity to operate the sensor autonomously without any electrical energy supply. Because the swelling and de-swelling are reversible processes, the device can be used both for switching on and off the contacts, respectively.

3 Model without axial forces

To calculate the deflection as a function of the hydrogel pattern, a simple mechanical model is used based on the beam theory for monomorph and bimorph beams (Marschner et al., 2014). Figure 2 shows the setup of the sensor and the corresponding mechanical model. The setup consists of the hydrogel-coated part of the bending beam with the torsional compliance n_B and the uncoated part of the bending beam with the torsional compliance n_P :

$$n_P = \frac{12l_P}{E_1 h_1^3 b}, \quad (1)$$

$$n_B = \frac{1}{b} \frac{12 \left(1 + \frac{E_2 h_2}{E_1 h_1} \right) l_B}{E_1 h_1^3 \left(1 + \frac{E_2^2 h_2}{E_1^2 h_1} + \frac{E_2}{E_1} \left(4 \frac{h_2}{h_1} + 6 \frac{h_2^2}{h_1^2} + 4 \frac{h_2^3}{h_1^3} \right) \right)}. \quad (2)$$

Hydrogels are much softer than silicon, steel or other spring materials, so that $E_2 \ll E_1$ applies. Considering that the hydrogel coating and the bending beam have the same thickness $h_1 = h_2$, Eq. (2) yields a good approximation:

$$n_B = \frac{12l_B}{E_1 h_1^3 b}. \quad (3)$$

The hydrogel-coated part of the setup acts as a torsional moment source M_{RH} when the relative humidity causes a swelling strain ε_{RH} :

$$M_{RH} = \frac{b}{2} \frac{E_1 E_2 h_1 h_2 (h_1 + h_2)}{E_1 h_1 + E_2 h_2} \cdot \varepsilon_{RH} \approx E_2 h_1^2 b \cdot \varepsilon_{RH}. \quad (4)$$

The swelling strain ε_{RH} results from the expansion coefficient α_{RH} of the hydrogel due to relative humidity φ_{RH} :

$$\varepsilon_{RH} = \alpha_{RH} \varphi_{RH}. \quad (5)$$

M_{RH} has to deflect both n_B and n_P , so that the overall torsional compliance n amounts to

$$n = \frac{n_B \cdot n_P}{n_B + n_P}. \quad (6)$$

According to Fig. 2c the deflection s results from the angle φ and the simplification that both parts of the setup are composed of lumped torsional springs with the deflected length $(l_B + l_P) = l/2$:

$$s = \frac{l}{2} \varphi = \frac{l}{2} n M_{RH}. \quad (7)$$

By inserting Eqs. (1), (2), (4) and (6), it yields the following:

$$s = 6 \frac{E_2 l^2}{E_1 h_1} \cdot \frac{l_B}{l} \left(1 - \frac{l_B}{l} \right) \cdot \varepsilon_{RH}. \quad (8)$$

Introduction of the degree of coverage x

$$x = \frac{l_B}{l} \quad (9)$$

leads to

$$s = 6 \frac{E_2 l^2}{E_1 h} \cdot x (1 - x) \cdot \varepsilon_{RH}. \quad (10)$$

Equation (10) shows that a maximum deflection can be achieved

- by a high ratio e_2/e_1 of Young's moduli of hydrogel and substrate (bending plate: silicon, steel),
- by thin bending plates,
- by large swelling strains ε_{rh} and expansion coefficients α_{rh} , respectively.

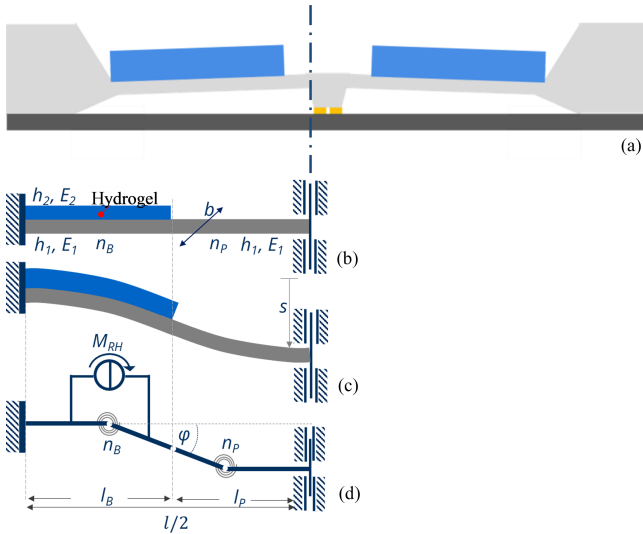


Figure 2. Model of the sensor switch of Fig. 1 without axial force, (a) setup, (b) bending beam partially coated with a hydrogel layer, (c) deflected sensor due to relative humidity changes, and (d) corresponding mechanical model. Shown is half of the sensor due to symmetry reasons (left: rigid clamping, right: vertically deflectable edge of the boss structure). n_B , n_P torsional compliance of the bending beam with and without hydrogel, respectively, l length, l_B length of the hydrogel-covered part, s deflection, φ angle of deflection at the transition point between the hydrogel-coated and the uncoated part, M_{RH} torsional moment due to the hydrogel swelling, b width, h thickness. Indices: 1 substrate (silicon, steel), 2 hydrogel, p substrate, b hydrogel/hydrogel-coated.

A maximum deflection s_{\max} is reached if $ds/dx = 0$, i.e. if the degree x of hydrogel coverage amounts to

$$x_{\text{opt}} = 0.5 \quad (11)$$

leading to

$$s_{\max} = \frac{3}{2} \frac{E_2}{E_1} \frac{l}{h} \cdot \varepsilon_{RH}. \quad (12)$$

For practical applications, one has to take into account

- that the model of Fig. 2d considers just a bending beam instead of usually used two-dimensional plates,
- that the model of Fig. 2b simplifies the setup by considering two lumped torsional springs and
- Eqs. (3) and (4) assume $E_2 \ll E_1$ and $h_1 = h_2 = h$.

For that reason, the optimum value $x_{\text{opt}} = 0.5$ of Eq. (11) might differ slightly. More general, a maximum deflection is obtained when the compliances n_B and n_P of the hydrogel-covered and non-covered parts are equal.

4 Model with axial forces

To avoid arcing and damage of the microcontact, the sensor has to switch quickly between the closed and opened state.

From this, the switching characteristic needs a hysteresis. This can be achieved when the bending beam is axially compressed by means of an axial force or by applying a source of expansion. To consider switching hysteresis properties, the model of Fig. 2 is complemented by an axial force F_A and an axially acting translational spring n_T (Fig. 3).

Figure 3 shows the corresponding model, based on the beam theory, of an axially compressed bending beam (Timoshenko and Gere, 2012). Here, for reasons of simplicity, the condition $l_B = l_P = l/4$ is assumed. From Fig. 3a, the deflection s_0 and the deflection angle φ_0 of the bending beam result from a source of expansion that leads to a length expansion of the bending beam part from length l_A to length l_B (Fig. 3b):

$$l_A = \frac{l}{4} + s_0 \frac{1}{4 \cos(\varphi_0)}, \quad (13)$$

$$l_B = \frac{l}{4 \cos(\varphi - \varphi_0)}, \quad (14)$$

where φ_0 and φ are the pre-deflection angle and the change of angle.

The resulting compression Δs yields

$$\Delta s = l_B - l_A = \frac{l}{4} \left(\frac{1}{\cos(\varphi - \varphi_0)} - \frac{1}{\cos(\varphi_0)} \right), \quad (15)$$

leading to an axial force

$$F_A = \frac{\Delta s}{n} = \frac{1}{n} \frac{l}{4} \left(\frac{1}{\cos(\varphi - \varphi_0)} - \frac{1}{\cos(\varphi_0)} \right). \quad (16)$$

For the derivation of the bending moment equation at equilibrium state, F_A was considered with its two vectorial components:

$$F_{Ax} = F_A \cos(\varphi - \varphi_0), \quad (17)$$

$$F_{Ay} = F_A \sin(\varphi - \varphi_0). \quad (18)$$

During swelling, the hydrogel-covered part acts as a bimorph providing a bending moment source M_{RH} depending on the humidity change. From Fig. 3b, the length change of l_B along the x direction results from the deflection angle $\varphi - \varphi_0$. The balance of torques yields together with Eqs. (16)–(18):

$$M_{RH} - F_{Ay} \frac{l}{4} + F_{Ax} \frac{l}{4} \tan(\varphi - \varphi_0) = 0. \quad (19)$$

For small deflection angles, the trigonometric functions in Eq. (19) can be expressed with the corresponding first terms of the Taylor series:

$$\sin(x) = x - \frac{x^3}{3!}, \quad (20)$$

$$\cos(x) = 1 - \frac{x^2}{2!}, \quad (21)$$

$$\tan(x) = x + \frac{x^3}{3}, \quad (22)$$

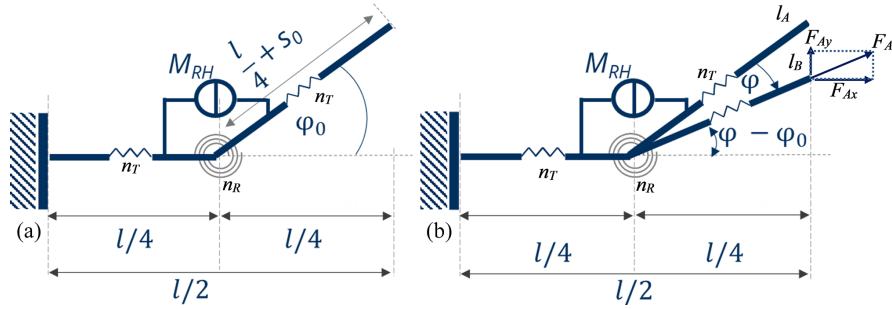


Figure 3. Mechanical model for a pre-deflected bending beam with length $l/2$, pre-deflection angle φ_0 , torsional spring n_R , translational spring n_T and humidity-dependent bending moment M_{RH} (a) without and (b) with axial compressive force F_A .

so that Eq. (18) becomes

$$M_{RH} - F_A \frac{l}{4} (\varphi - \varphi_0) + F_A \frac{l}{4} (\varphi - \varphi_0)^3 = 0. \quad (23)$$

Regarding Eq. (4), M_{RH} is proportional to ε_{RH} and, hence, to relative humidity φ_{RH} , where φ_{RH} is proportional to the deflection s . This allows us to re-write Eq. (23):

$$M_{RH} - A(\varphi - \varphi_0) + B(\varphi - \varphi_0)^3 = 0 \quad (24)$$

and respectively

$$\varphi_{RH} - A^*s + B^*s^3 = 0. \quad (25)$$

A and B as well as A^* and B^* are coefficients to be calculated from M_{RH} and F_A via Eqs. (4), (5) and (15). Figure 4a shows the curve progression of φ_{RH} versus $(\varphi - \varphi_0)$ for varying parameters A^* and B^* . For $A^* = 1$ and $B^* = 0$, the curve progression shows a linear dependency of φ_{RH} on $(\varphi - \varphi_0)$. For $A^* = 1$ and $0.2 < B^* < 0.9$, a hysteresis occurs and for $A^* = 1$ and $B^* = 1$ a switching without a hysteresis was found. As a consequence, by varying both the bending beam geometry and the material parameters, the shape of the curves and the width of the hysteresis can be adjusted. In Fig. 4b, the S-shaped curve progression with switching hysteresis is shown for $A^* = 1$ and $B^* = 0.5$ depending on the relative humidity with the switching points from s_1 to s_2 and from s_3 to s_4 , respectively, and the curve progression without switching hysteresis for $B^* = 1$ and $B^* = 0$.

5 Fabrication of a sensor switch with switching hysteresis

To ensure that the electrical microcontacts are reliably closed and opened, oscillations between the opened and closed states as well as local electric field strength peaks that are too high and associated arcs have to be avoided. This can be achieved by implementing a switching hysteresis between two stable states (Chen et al., 2008).

To demonstrate the concept, a beam-like sensor switch was manufactured from sheet metal, an easy-to-process material, with Young's modulus of $2.06 \times 10^{11} \text{ N m}^{-2}$ (Fig. 5a)

Table 1. Material and geometry parameters of the beam-like sensor switch with switching hysteresis (DIN EN 10270-1, 2012; Bellmann, 2016).

Parameter	Sheet metal (n_B, n_P)	Hydrogel
Length (m)	0.025	0.025
Width (m)	0.012	0.012
Thickness (m)	3×10^{-5}	3×10^{-5}
Young's modulus (N m^{-2})	2.06×10^{11}	3.5×10^9 at 5 % RH 3×10^8 at 90 % RH

(DIN EN 10270-1, 2012). As shown in Fig. 5b, the bending beam was fixed in a fixation and axially clamped by means of an adjusting screw.

The humidity-sensitive hydrogel layer (thickness $3 \times 10^{-5} \text{ m}$) was structured on the top of the metal sheet. To achieve sufficient adhesion the metal surface was pre-treated by means of a chemical cleaning process and an adhesion-promoting agent. For that, the bending beam was cleaned in a solution made of distilled H_2O , 25 % ammonia and 25 % peroxide (2 : 1 : 1) at 358.15 K for 900 s. Afterwards, the bending beam was pre-treated in a plasma etching system (VTD: DREVA 450) with oxygen plasma at a pressure of 15 Pa at 400 W for 300 s. Then a 3 mL solution of the adhesion-promoter agent made of 0.9 mL (3-Aminopropyl)triethoxysilane (APTES) and 99 mL H_2O was applied to the plasma-treated surface and heated in an oven at 373.15 K for 600 s (Gartmann, et al., 2010).

The moisture-sensitive hydrogel was made from a blend of 15 wt % poly(vinyl alcohol) (PVA, molecular mass $M_w = 89000 \dots 98000$) and 7.5 wt % poly(acrylic acid) (PAA, $M_w = 450000$) in a mass ratio of 4 : 1. Both materials were purchased from Sigma-Aldrich. The powders were solved in deionized water and mixed for several hours for PAA at 343.15 K and for PVA at 353.15 K until homogenous solutions were formed. Then both polymer solutions were mixed for several hours at 323.15 K to form the hydrogel blend (Jose et al., 2014). The hydrogel layer was deposited by a

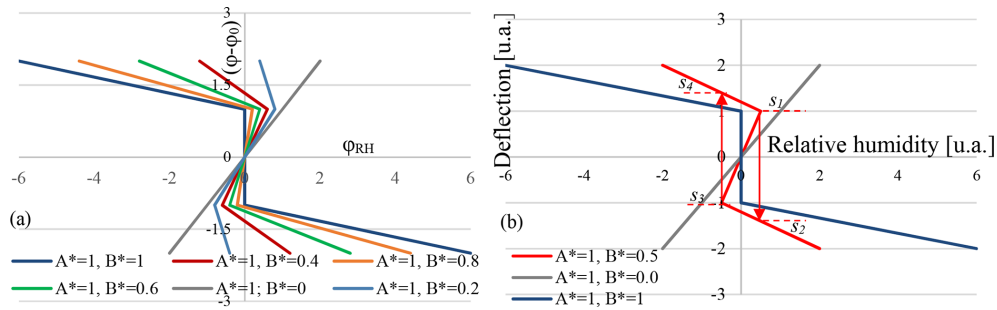


Figure 4. Calculated curves for (a) deflection s and (b) angle $\varphi - \varphi_0$ versus relative humidity ϕ_{RH} . The switching points ($s_1 \rightarrow s_2$; $s_3 \rightarrow s_4$) are marked.

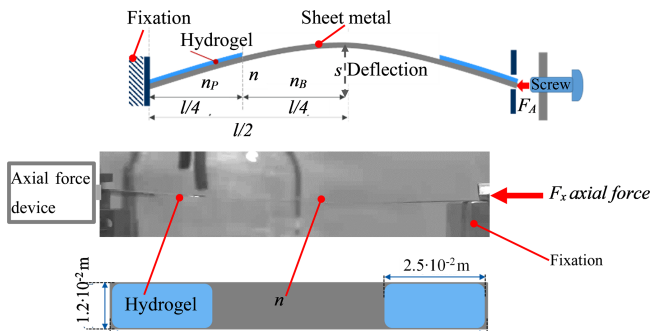


Figure 5. Beam-like sensor switch with switching hysteresis: (a) sensor setup with axial clamping, (b) cross-sectional and (c) top view of the setup. Hydrogel PVA/PAA, material and geometry parameters as in Table 1.

pipette of a 5 mL polymer solution, consisting of PVA/PAA, to the prepared surface with respect to the optimum coverage ratio of $x = 0.5$ and dried at 295.15 K for 21600 s. Figure 5c shows exemplarily the structured hydrogel layer on the bending beam surface. After drying, the polymer was thermally cross-linked in an oven at 393.15 K for 1200 s (Arndt et al., 1999).

6 Deflection measurements of the sensor switch with switching hysteresis

The hydrogel-coated bending beam was axially clamped in a fixation (Fig. 5). A compression load of 0.04 N was applied by means of an adjusting screw. For its measurement, a force-measuring device (SAUTER FC 10) was applied on the opposite side of the fixation. The beam-like sensor switch was investigated in a self-made humidity chamber. The humidity was varied using a bubble system and was monitored by means of a humidity sensor (Hygro-Thermometer, B+B). The deflection of the pre-deflected bending beam was recorded via a CMOS camera (HIKVISION).

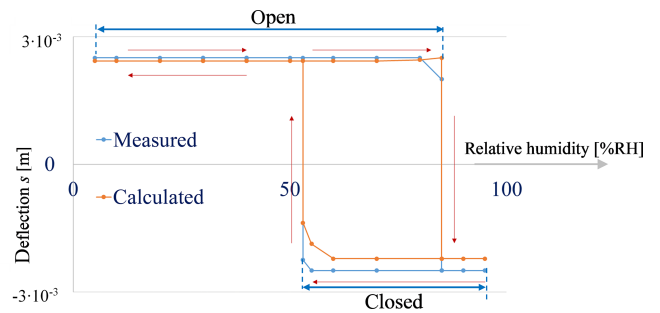


Figure 6. Deflection of the bending beam with structured hydrogel as function of the relative humidity. The resulting switching hysteresis shows two switching points at 53 % RH and 85 % RH.

7 Experimental results

Figure 6 shows the measured deflection of the bending beam as a function of the relative humidity in the range from 5 % RH up to 95 % RH. Above 85 % RH, the bending beam abruptly switches from the pre-deflected side to the opposite side. At 53 % RH, by changing from the humid to the dry environment, the beam switches back to the initial state demonstrating successfully the switching hysteresis.

To compare the experimental results with the mechanical model, the material properties and the geometry parameters from Table 1 are inserted into Eq. (22). The deflections of the bending beam s as function of the relative humidity are calculated from Eq. (7). In comparison to the measured data, the calculated deflection shows a deviation of 8 %, whereas the measured hysteresis width of the switching curve shows a good agreement.

8 Summary and outlook

This work deals with the development of a sensor switch with switching hysteresis for humidity sensing. The hysteresis is needed for the safe and reliable switching, i.e. fast opening and closing of the contacts. Based on the beam theory, a mechanical model was derived to calculate the deflection s depending on the degree of coverage $x = l_B/l$, i.e. of the

length ratio of the partly hydrogel-coated bending beam part to the total length of the bending beam. It could be shown that a maximum deflection is achieved when the stiffness of the hydrogel-coated part and the uncoated part are equal, i.e. when the lengths of the coated and uncoated parts of the beam are equal ($x = 0.5$). To include the switching hysteresis in the mechanical model, it was complemented by an axial force F_A and the axial compliance n_T . From this, it could be shown that the width of the switching hysteresis is adjustable via variation of the geometry parameters, like the thickness or the length of the bending beam. To prove the mechanical model, a beam-like sensor switch was manufactured by means of a metal sheet covered with a hydrogel layer at a coverage degree of 0.5 and the switching hysteresis was successfully demonstrated.

Data availability. The data presented in this article are stored in an internal system according to the guidelines of the DFG.

Author contributions. The authors NG and GG designed and developed the experimental setup. NG and GG developed the mechanical model to describe the sensor switch. NG performed the experiments, analyzed the data, and wrote the initial paper. GG revised the paper and led the project. Both authors approved the final paper.

Competing interests. The authors declare that they have no conflict of interest.

Special issue statement. This article is part of the special issue “Sensors and Measurement Systems 2019”. It is a result of the “Sensoren und Messsysteme 2019, 20. ITG-/GMA-Fachtagung”, Nuremberg, Germany, 25–26 June 2019.

Acknowledgements. The author would like to thank his supervisor Gerald Gerlach for his support.

Financial support. The authors were supported by the Deutsche Forschungsgemeinschaft (DFG) for financial support within the Hydrogel-based Microsystems Research Training Group (GRK 1865).

Review statement. This paper was edited by Eric Starke and reviewed by two anonymous referees.

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