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Resonant micromechanical fiber optic sensor of relative humidity

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ABSTRACT

This paper presents a novel type of humidity sensor which is based on silicon micromechanical resonant structure with an attached silica gel granule. The mechanical oscillations of microstructure are interrogated with the aid of fiber-optic Fabry–Perot interferometer. The output signal of such a sensor in the frequency form is not sensitive to long-term variations of the optical power and it can be easily digitized by counting the periods. Two-channel PLL was used for the first time to track the resonant frequency at any interferometer working point position. The design of a sensor turned out to be rather successful: the mass of the air moisture absorbed by silica gel granule turned out to be dependent linearly on the relative humidity in the range from 0% to 75% that simplifies the calibration of the sensor; and the high quality factor of the mechanical resonator allowed us to resolve the resonant frequency with precision about 0.1 Hz, which corresponds to sensor threshold sensitivity in 0.02% of relative air humidity.

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1. Introduction

Resonant micromechanical structures have been proposed and demonstrated for a number of various fiber-optic sensors (FOS) [1,2,8]. The output signal of such sensors in the frequency form presents two major advantages: it can be transmitted through an extended system and over a large distance without any error and, second, it can be easily digitized by counting the periods. Detection of resonator oscillation is often carried out with the use of a fiber-optic Fabry–Perot interferometer formed by the output end of the fiber and the partially reflecting resonator surface. In this case the sensitivity of the oscillation registration system is subnanometer. So small amplitude of resonator oscillation can be excited purely optically by modulated optical radiation [2–6], which makes the sensitive element electrically passive, as it does not contain any electronic circuits and components, and hence the sensor can be used in the areas of high explosiveness and strong electromagnetic interferences.

Micromechanical resonant structures are fabricated by anisotropic etching of silicon or other semiconductor materials and have in many cases the form of a microbeam clamped at both ends. The main problem here is to achieve a high sensitivity to the parameter of interest and avoid a strong cross-sensitivity to temperature, pressure and mechanical stresses. In our work we used the micromechanical structure in the form of a movable square part supported by flexible silicon beams only from one side. In such a construction the variations of the temperature and deformation of the substrate under the action of the ambient pressure and forces do not induce a internal stress inside the supporting beams and consequently do not influence the resonance frequency of microstructure to such extend as it happens in microbridge resonators.

FOS of humidity developed earlier were based generally on the variation of the wavelength or intensity of the light

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under the action of the measured parameter [7,8]. We describe here a novel method for measurement of relative humidity by the resonant frequency of a micromechanical structure with silica gel. This method allows to achieve high sensitivity and precision of the sensor to the relative humidity, while the dependence of the moisture mass absorbed by silica gel on the relative air humidity was found to be linear, which simplifies sensor calibration. Within the accuracy of the experiment we found no hysteresis in the sensor readings, as well as its output signal did not depend on the ambient temperature. The relative humidity can be measured by this method at temperatures below freezing too.

2. Sensitive element

Mechanical resonator used in the sensor was fabricated by anisotropic etching in ⟨1 0 0⟩ boron doped silicon wafer. It consists of the square part 2000 × 2000 μm mounted on two supporting beams, 50 μm thick, 650 μm wide and 500 μm long, as shown in Fig. 1. Entire structure has the size 7000 × 7000 × 385 μm. The square part can move slightly in the direction perpendicular to the structure plane bending the supporting beams.

Technological route included deposition of Si_3N_4 to the both sides of the polished silicon wafer, reactive ion etching of Si_3N_4, laser wafer marking, resist plasma-stripping, chemical resist stripping and chemical anisotropic etching. 1st photomask formed the entire structure and alignment marks from one side of the wafer, while 2nd mask is applied from the opposite side of the wafer and it formed the supporting beams of necessary thickness. Some of the structures fabricated had the narrow strips of Si_3N_4 between the movable part and surrounding frame (see SEM image in Fig. 2).

The upper surface of the mechanical resonator acts as one of the mirrors of the Fabry–Perot interferometer (we did not use any metal coating of the resonator, silicon surface with Si_3N_4 layer reflects enough light). On the other side of the movable part a silica gel granule of diameter about 2 mm was attached, which absorbs the moisture from the air and ensures by such a way the sensor's sensitivity. Silica gel is one of the best synthetic adsorbents. The porous structure of interconnected voids creates a significant surface area (up to 1000 $m^2\,g^{-1}$), while the volume of all pores may reach 0.5–1.2 mL/g with a predominance of pores of diameter from 5 to 15 nm. Silica gel can absorb from the air or other gases the moisture, which is about 40% of its own weight. The equilibrium amount of moisture absorbed depends on the relative humidity of the ambient gas.

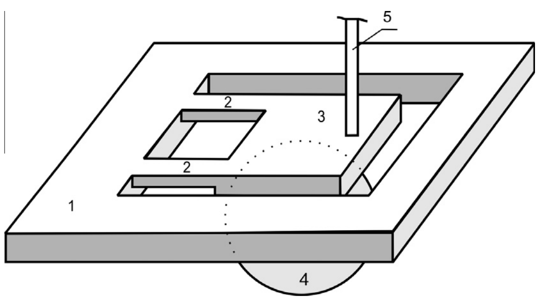

Fig. 1. The scheme of silicon microstructure which was used in a sensitive element.1 – surrounding frame, 2 – support beams, 3 – movable part, 4 – silica gel granule, 5 – optical fiber.

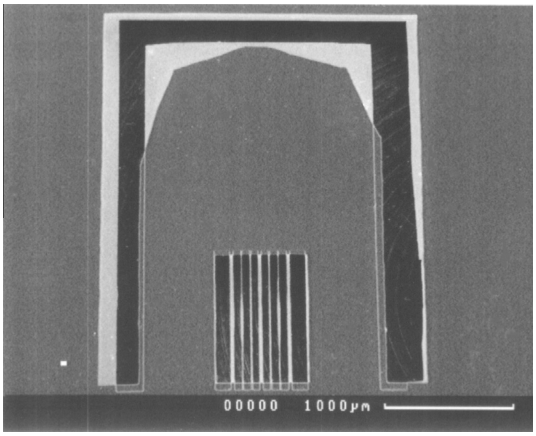

Fig. 2. Silicon resonant microstructure with narrow strips between movable part and the frame under scanning electron microscope.

The greater the relative air humidity, the greater the mass of silica gel granule and the lower the natural frequency of the resonator f:

$$f = f_0\left(1 + \frac{\Delta m}{m + m_1}\right)^{-1/2} \quad (1)$$

where f_0 is the resonant frequency of microstructure at zero humidity, Δm is the mass of the moisture absorbed by silica gel granule, m_1 is the mass of the moving element of silicon microstructure without silica gel granule, m is the mass of silica gel granule without a moisture (at zero humidity). The value of f_0 can be easily found from the experimental points by extrapolation to zero humidity. Measurement of the resonant frequency f_1 of the silicon microstructure without silica gel granule allows to estimate the ratio $\Delta m/m$ as follows:

$$\frac{\Delta m}{m} = \frac{(f_0/f)^2 - 1}{1 - (f_0/f_1)^2} \quad (2)$$

3. Interrogation of mechanical oscillation with fiber-optic interferometer Fabry–Perot

The oscillation of resonator was detected with the aid of the fiber-optic interferometer Fabry–Perot formed by the output end of the optical fiber and partially reflecting surface of the movable part of the micromechanical structure. The interferometer is illuminated with a CW laser source of intensity I_0 and wavelength λ. The oscillation of the mechanical resonator changes the distance x_0 between interferometer mirrors and hence the intensity of the light reflecting back into the fiber is modulated at the frequency of resonator oscillation. The intensity reflection coefficients of the fiber end and the resonator surface are r and R respectively. Summing the geometric series of the ampli-

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