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Analytical Investigations Involved in a Microcantilever for Gas Detection

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Abstract: *MEMS has been identified as one of the most promising technologies for the 21st Century and has the potential to revolutionize both industrial and consumer products by combining silicon-based microelectronics with micromachining technology. Its techniques and micro system based devices have the potential to dramatically change all of our lives and the way we live. A cantilever is the simplest mechanical structure and hence it gains its significance. In the cantilever sensors the basic principle of measurement would be by measuring the change in resonant frequency or the peizoresistivity based on the displacement. The Resonant frequency is the frequency that produces the maximum displacement that a vibrating body can achieve. The change in resistance value of a conductor due to applied force resulting in strain and displacement is called piezoresistive effect. This paper briefs about the analytical aspects in designing a microcantilever. Initially the modelling of the cantilever is dealt followed by the mandatory equations for both the frequency and resistance measurement. Followed by the the ppmv to mass conversion, so that we can effectively incorporate it in the gas sensing stream. The microcantilever as a gas sensor has wide applications.*

Keywords: *Cantilever, resonant frequency, piezoresistance*

Introduction:

Numerous components and devices from calculators to mobile phones and computers applied in our daily lives are fabricated using microtechnology. In sensor applications the expectations are a robust, reliable, inexpensive, portable device with low power consumption. A microcantilever fits into this as the simplest device which could be easily fabricated. Any mechanical structure will have an inherent resonant frequency. The fundamental operation of a cantilever will be that when a force is applied at the free end the cantilever will deflect creating a strain across its surface, it means that there would be a displacement from the original position and the inherent frequency will also be altered. Thus depending on the force applied the resonant frequency changes and the resistivity changes. These are the factors which are to be determined to infer the amount of force that is applied. The resonant frequency can be determined by applying an a/c signal to the cantilever and making it vibrate and then check for the amplitude. The piezoresistance can be obtained by connecting the cantilever resistor across in a wheatstone bridge setup and checking for the imbalance. The analytical investigations will help in verifying the experimental results and will also help us in optimization before going for the fabrication process.

Analytical Investigations:

Modelling Theory of a microcantilever

A cantilever is a simple beam with one end fixed and the other free. The equivalent mechanical model of this cantilever beam is a mass with spring and frictional element illustrated in Fig.1.

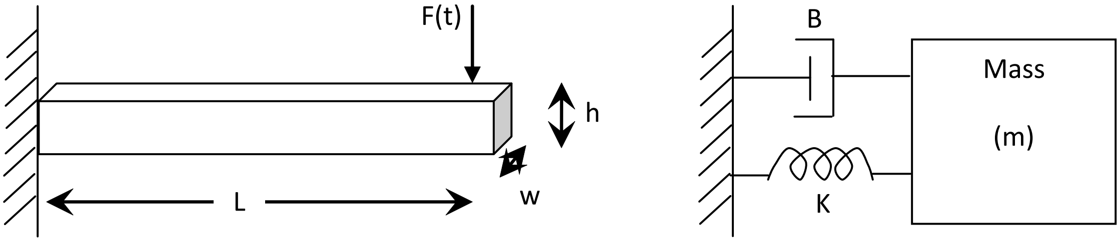

Figure 1: a) Idealization of a cantilever b) Equivalent mechanical model

The general equation of the mechanical model is

$$m\frac{d^2x}{dt^2} + B\frac{dx}{dt} + Kx = F(x,t)$$

Sensing Methodology:

Resonant Frequency Determination:

Resonant frequency is dependent on the spring constant and mass of the body. This means that any change in spring constant or the mass of the cantilever will change the resonant frequency of the cantilever. The frequency shift measurement can help us determine the amount of mass change assuming the spring constant as a constant. Even 0.7 picogram of mass change could be detected (Madou, 2002)

This is a simple homogenous equation and when there is no damping B becomes zero and finally the solution becomes

$$\omega = \sqrt{\frac{K}{m}}$$

We know ω = 2пf , hence

$$f = \frac{1}{2n}\sqrt{\frac{K}{m}}$$

Sensitivity is defined as a function of the frequency shift and the mass shift i.e the ability of the cantilever to detect shifts in the frequency.

$$S = \lim_{\Delta m \to 0} \frac{1}{f}\frac{\Delta f}{\Delta m} = \frac{1}{f}\frac{\partial f}{\partial m}$$

Where f is the initial frequency, Δf and δf are finite and infinitesimal changes in frequency and Δm and δm are the changes in mass.

Piezoresistance Determination:

The displacement of the cantilever creates a stress on it, using Stoney's equation the displacement is derived as a function of the differential surface stress

$$\delta = \frac{3L^2(1-\upsilon)}{Et^2}\,(\sigma_1 - \sigma_2)$$

where δ is the displacement of cantilever, υ is the Poison's ratio, E is the Young's modulus, $(\sigma_1 - \sigma_2)$ is the differential surface stress, L is the length and t is the thickness of the cantilever beam.

The stress is maximum at the surface of the cantilever near the base and can be calculated as

$$\sigma_{max} = \frac{6L}{Wt^2}\,F = \frac{3Et}{2L^2}\,\delta$$

Where F is the applied force and W is the width of the cantilever beam

The resulting fractional resistance is

$$\frac{\Delta R}{R} = \pi_l \sigma_{max} = \beta\,\frac{3\pi_l(1-\upsilon)}{t}(\sigma_1 - \sigma_2)$$

The resistance change has to be measured and this is achieved by connecting the peizoresistor in a wheatstone bridge setup as shown in Fig.2

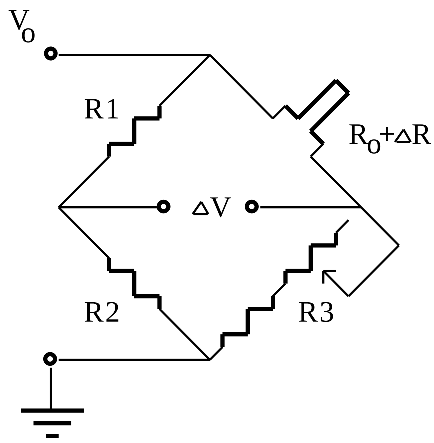

Fig. 2 Wheatstone bridge

The output of a Wheatstone bridge is given by

$$\Delta V = V_0\left\{\frac{R_2}{R_1+R_2} - \frac{R_3}{R_0+\Delta R+R_3}\right\} \Rightarrow R_0 + \Delta R = R_3\left\{\frac{V_0(R_1+R_2)}{R_2V_0 - \Delta V(R_1+R_2)} - 1\right\}$$

The sensitivity is dependent of this voltage output.

Converting ppm to mg/m^3

To calculate the force exerted on the cantilever we must first know the mass equivalent mg/m^3 of the gas molecules concentration in ppmv. Supposing the current concentration of carbon dioxide in atmosphere is 400 ppmv, to express this number in mg/m^3 at a pressure of 1 atmosphere (101,325 Pa) and at a temperature of 298.15 K. The starting place is the definition of ppmv:

400 ppmv CO_2 = 400 x 10^{-6} m^3 CO_2/ 1 m^3 air.

It is easier to convert moles to mass, hence to know how many moles of CO_2 are present, the ideal gas law is rearranged:

n = PV/RT

substituting the values in SI units:

n = (101,325)(400 x 10^{-6})/(8.31441)(298.15)

Also consider:

(Mass of CO_2 in grams) = n * (molecular mass of CO_2 in grams)

The molecular mass is simply the sum of the atomic masses (12.01 + 2*16.00= 44.01 grams)

Mass of CO_2 in grams = (44.01)(101,325)(400 x 10^{-6})/(8.31441)(298.15) = 0.7196 g

So, at 1 atm and 298.15 K,

400 ppm CO_2 = 720 mg/m^3 CO_2

This conversion will help us to determine the force to be applied for simulation and also to calculate the ppm of gaseous molecules present.

Conclusion

The analytical investigations needed for a microcantilever has been presented. Initially the microcantilever was modelled followed by the two sensing methods and finally ends with the conversion factor. The various parameters needed for the determination of the concentration of gas has been dealt. This concludes with the preliminary ideas involved while designing a gas sensor.

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