

High Sensitive Mass Detection using GaAs Coupled Micro Resonators

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Abstract: This work demonstrates the improvement of mass detection sensitivity and time response using a quite simple structure of sensor. Indeed, complicated technological processes are often required to reach high sensitivity when we want to detect specific molecules in biological fields. These developments constitute an obstacle to the early diagnosis of diseases. An alternative is the design of coupled structures. The device is based on the piezoelectric excitation and detection of two GaAs micro structures vibrating on antisymmetric modes. GaAs is a material which has the advantage to be micromachined easily using clean room processes. Moreover, we showed its high potential in direct biofunctionalisation to be used in biological field. A specific design of the device was performed to improve the detection at low mass and an original detection method has been developed. The principle is to exploit the variation in amplitude at the initial resonance frequency which has in the vicinity of weak added mass the greatest slope. Therefore, we get a very good resolution for an infinitely weak mass: relative voltage variation of 8%/1fg. The analysis is based on results obtained by finite element simulation.

Keywords: GaAs piezoelectric transducer; acoustic coupling; high sensitivity;

1. Introduction

Low mass detectors are becoming highly desirable, mainly in the biology and environment fields to detect small objects, like molecules or atoms [1-3]. For example, the field of biology requires mass detectors with a high resolution, especially in the range [1zg, 10fg], to detect the presence of particles

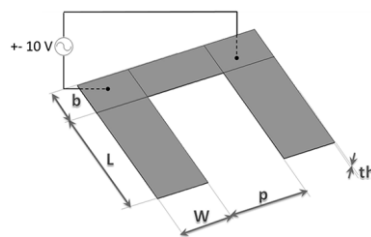
(grafting onto a surface, deposition, adsorption). However, measurement mass techniques by conventional sensors require an important miniaturization to get sensitivity in the zeptogram range [1-6]. These manufacturing techniques are complicated to develop and control. Moreover, the sensing structures will reach a nanometer size and then will become very brittle. That's why coupled sensor networks arouse, since recently, a particular enthusiasm [7-15]. Coupled structures present also other advantages such as the opportunity to perform on the same substrate differential measurements or to obtain a multiplexed analysis of a biological or chemical solution. The choice of GaAs as the material for the transducer is due to first a good knowledge of its microfabrication technology and second to the opportunity to biofunctionalize this material. In parallel, we proved the biocompatibility of GaAs surface for in vitro analysis [16-18]. The work presented here constitutes one of the preliminary steps necessary before the integration of electronics and transducers arrays on the same substrate for biological field measurements. The paper is divided into three sections. First, we present the principle of the coupled resonators and the usual method of mass measurement. In the second section, we compare different methods of analysis to improve the sensitivity and time response. Finally, we propose the design of our device.

2. Measurement principle and results

2.1 Principle

We consider a tuning fork in GaAs crystal with coupled resonant cantilevers vibrating on an antisymmetric bending mode. The size of the device is given on figure 1. With this geometry, the resonance frequency f_R is obtained at $f_R = 109\text{kHz}$.

Figure 1. Design of the coupled microcantilevers. $L=25\mu\text{m}$, $w=10\mu\text{m}$, $th=0.1\mu\text{m}$, $p=20\mu\text{m}$ and $b=8\mu\text{m}$



The frequency response is performed to identify, without and with added mass, the maximum amplitude of the resonance peak. The usual method consists in the experimental determination of the frequency shift Δf of the resonance frequency f_R with the added mass Δm . The expression of Δf is given in equation (1). It depends on the resonator mass m and we can observe that the increase of sensitivity passes through a decrease of mass. So, the variation of amplitude Δu is an image of the added mass Δm in a quasi-linear function as seen in equation (2). This last method is preferred to the frequency shift determination if $k_c < k/2$.

$$\frac{\Delta f}{f_R} \approx \frac{\Delta m}{2 \times m} \quad (1)$$

$$\frac{\Delta u}{u_R} \approx \frac{\Delta m \times k}{4 \times k_c \times m} \begin{cases} k_c : \text{coupling spring} \\ k : \text{cantilever spring} \end{cases} \quad (2)$$

We performed calculation on an antisymmetric bending mode for which the amplitude variation is higher than that of the symmetric mode. As well as in the publication of E. Gil-Santos et al [12], we observed a quasi-linear decrease of the amplitude as a function of the added mass. We obtained in the range [0, 150 fg], a linear relative variation in resonance peak amplitude of 8000 ppm/fg against 2 ppm/fg for the relative variation in resonance frequency. These values confirm the advantages of the amplitude method for coupled microcantilevers.

Nethertheless the sensitivity is not sufficient to detect biological molecules. We propose to improve the performance using different methods to exploit the frequency versus mass spectrum.

2.2 Methods of analysis for resonant amplitude versus frequency curves

In the previous section, we propose two methods:

- A-Method: determination of the frequency shift with added mass.
- B-Method: determination of the amplitude at the resonance peak by frequency sweeping.

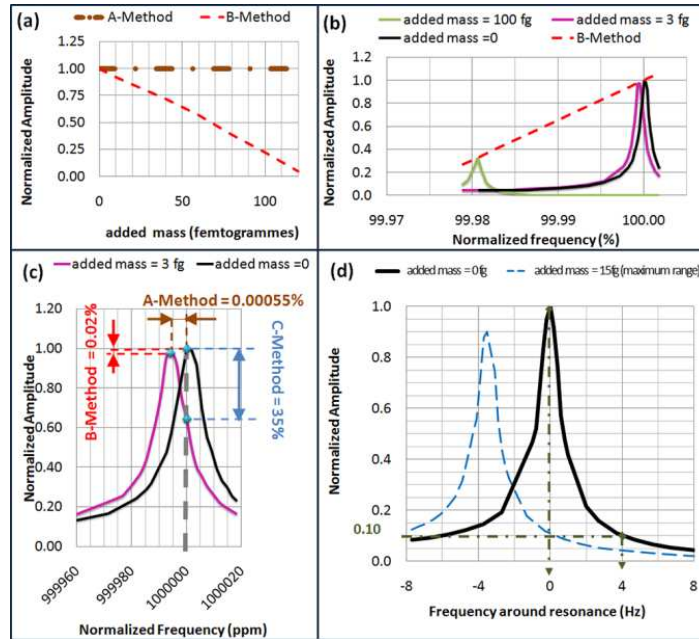
Fig. 2(a) shows the evolution of Δf and Δu with Δm . As already say, the relative variation of amplitude is a better method in the case of coupled cantilevers. As seen on Fig.2(b) we have an overlap of resonance peak for a very weak added mass and so, it remains difficult to reach the required sensitivity. To improve performances using the same measurements principle as previously, we propose, for very weak mass to determine the variation of the amplitude at the fixed frequency f_R where f_R is the resonant frequency at the initial weight m . This method is called C-method. Compared to A and B-methods, a significant increase of the relative variation in the amplitude is obtained (Fig.2(c)). Moreover, as the frequency sweep can be omitted, the measurement process is easier and the acquisition time shorter.

It is clear that the higher the quality factor, the higher the sensitivity of the transducer. The operating range which is one of the criteria for transducer characterization is given by equation (3). It can be deduced from the initial microcantilever mass m , the resonance frequency of the selected mode f_R and the half-width of the resonance peak at 10% of the relative variation in amplitude.

$$Range \approx \frac{m \times \Delta f_{(\Delta \text{relative amplitude change} = 10\%)}}{f_R} \quad (3)$$

The C-method is valid as long as there is a monotonic overlap of the resonance peak with added mass on the resonance characteristic at initial weight. In the case of Fig.2(d), we have $\Delta f_{(\Delta \text{relative amplitude change} = 10\%)} = 4$ Hz and the operating range is equal to 15 fg. It may be noticed that if the resonance curve has a better quality factor, then the resolution increases but the operating range decreases. As the operating range is too tiny, we propose to use a hybrid method to exploit the good performances of C-method when we are concerned with very weak added mass. It consists without modifying the device to use B-method when the added mass is over the operating range. With our device, the threshold for switching between the two methods is for $\Delta m = 15$ fg which corresponds to a relative variation in the maximum deflection of 11.5%.

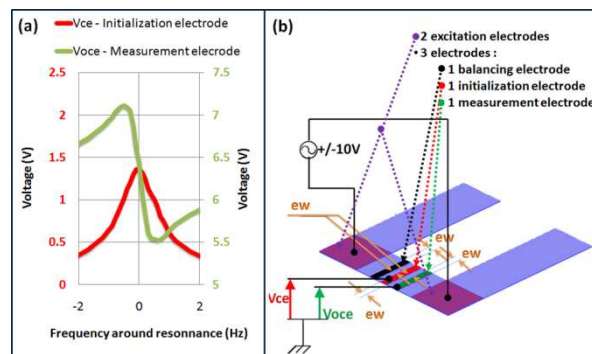
Figure 2. (a) B-method / A-Method vs added mass: comparison between the relative variation of the maximum amplitude of the beam deflection and the relative variation of the frequency shift of the resonance peak. (b) Amplitude without and with added mass vs frequency. (c) Zoom on the overlap shown in (b). We exploit the resonance peak overlap to obtain a higher resolution with C-method than with A and B methods. (d) Amplitude vs frequency around resonance frequency: determination of the sensor range.



2.3 Design of the device

To adapt the previous methods we used a device with a piezoelectric excitation and detection. The main advantage of the piezoelectric measurement with respect to the optical one is to be able to obtain a resonance peak with the appearance of an even or odd differentiable function according to the electrode position on the coupling element. According to a study parameterized in frequency on the voltage change within the coupling element, we determined that we need to deposit an electrode at the coupling element center of the microcantilevers. As shown in Fig.3(a), this electrode gives a response with an even function. Nevertheless, an off center electrode provides an odd function. As the tangent at zero of an odd differentiable function is significantly greater than an even differentiable function, it's undeniably preferable to exploit the response of the off center electrode for an infinitely weak mass following the C-method. The device (Fig.3(b)) is then composed of three electrodes, the balancing electrode keeping the symmetry of the device.

Figure 3. (a) Frequency analysis of voltage signals V_{ce} and V_{oce} . (b) Piezoelectric excitation and detection with three electrodes placed at regular intervals and centered on the coupling element.



With this device, we obtained in the range from 1zg to 0.1fg a resolution 36 times higher than with the B-method. This corresponds to a relative variation in voltage of 8%/fg with is a very good sensitivity for the infinitely weak mass according to the size of the device. To expand the operating range we used as already seen the hybrid method of analysis.

3. Conclusions/Outlook

To conclude, we have shown that the sensitivity of mass sensors based on coupled cantilevers can be significantly enhanced by a thorough analysis of the measurement. We have proposed and demonstrated the benefit of an analysis method which significantly increases the resolution for the addition of very weak mass on coupled microcantilevers. Moreover, utilizing such a method for mass detection offers a real advantage over the more conventional resonant frequency shift approach and the maximum amplitude method. Indeed, thanks to this attractive method of analysis, the fabrication of highly miniaturized devices can be avoided. Optical and piezoelectric detections have been considered and compared in terms of sensitivity at very weak added mass. The proposed method is particularly efficient for piezoelectric detection using appropriate electrodes design. The results with this method are very promising and the device remains easily to microfabricate. In the future, we like to achieve coupled sensors whose structure is based on membranes instead of beams to change the mode of vibration, increase the resonant frequency and improve the quality factor.

Conflicts of Interest

The authors declare no conflict of interest.

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