研 究 速 報

Resonant-type Micro-probe for Vertical Profiler

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1. INTRODUCTION

Nowadays, microfabrication techniques such as Micro-Electro-Discharge-Machining (Micro-EDM) or Micro-Ultrasonic Machining (Micro-USM), allow the micromachining of holes, typically 100μm in diameter and 1mm in depth. Manufacturing of such micro-holes has led to a new problem of characterization. Indeed, to our knowledge, the existing characterization tools, including stylus profilers and optical profilers, are not suitable for the measurement of the inner dimensions (diameter and profile) along the depth of these high aspect ratio structures.

A solution to this problem is to use long and thin probes (Fig. 1), whose dimensions are typically 1 millimeter in length with a cross-section area of about 20x10μm^2. An actuating element as well as a sensing element has to be associated to the probe so that it can be moved or vibrated, with the simultaneous measurement of the contact force. From this point, several solutions are possible, depending on the nature of the actuating and sensing elements as well as on the measurement methodology.

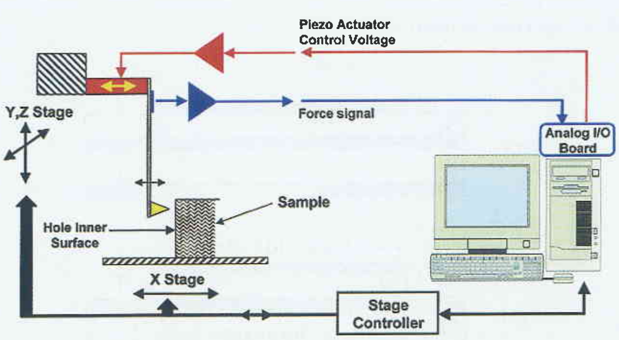

Fig. 1 Vertical profiler for the measurement of inner dimensions of micro-holes.

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Surface profiles are obtained through the measurement of the deflection at the end of a cantilever beam, which scans over the hole inner surface. The earlier version of micro-probes used electrical contact method for detection of the mechanical contact with the sample [1]. We are now developing 2 new types of probes: the piezoresistive-type probes, and the resonant-type probes. In this paper, the emphasis is put on the resonant type probes. They use the stress-induced frequency shift of a resonator for the measurement of the cantilever deflection when it touches a surface.

2. PROBE SENSING METHODS

2.1 Probes based on electrical contact

A first solution for vertical profile measurement was successfully tested in our previous work. It is the so-called vibroscanning method [1]. In this method, the probe is vibrated (with a piezo-actuator) near the surface to be measured. The contact is detected through an electrical contact between the probe and the surface when the sample is made of a conducting material, or between twin probes in the case of insulating samples.

2.2 Piezoresistive-type probes

The piezoresistive device is schematically depicted in Fig. 2. A picture is shown in Fig. 3. It consists of a silicon thin cantilever. SOI wafers are used to control the cantilever thickness. A piezoresistive gage bridge is integrated near the clamping. It consists of a) four p-type diffused piezoresistor and b) a metallization for the association of these resistors in a Wheastone bridge configuration and also for the contact pads. The cantilever deflection creates a stress in the clamping area, which modifies the value of the resistors, and then, an output voltage difference is generated in the Wheastone bridge. The typical sensitivity expected with such device is 10mV/μm.

2.3 Resonant type probes

Resonant-type probes use the stress-induced frequency shift of a resonator for the measurement of the cantilever deflection when it touches the surface of the sample. The device is schematically depicted in Fig. 4. A cantilever beam is attached to two compliant bridges, which are associated to comb-drives, so that they can work as resonators. When the cantilever touches the surface of a sample, its deflection causes stresses σ with opposite signs in the two bridges. As a result, changes in resonance frequency occur. Tensile stress in the first bridge leads to an increase of its resonance frequency while compressive stress leads to a decrease of resonance frequency of the second bridge. Furthermore, the design was chosen so that the working mode is the first resonance mode. This mode corresponds to minimum vibration amplitude at the end of the probe.

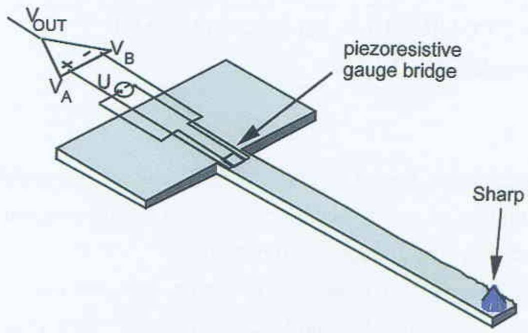

Fig. 2 Structure of the piezoresistive probe.

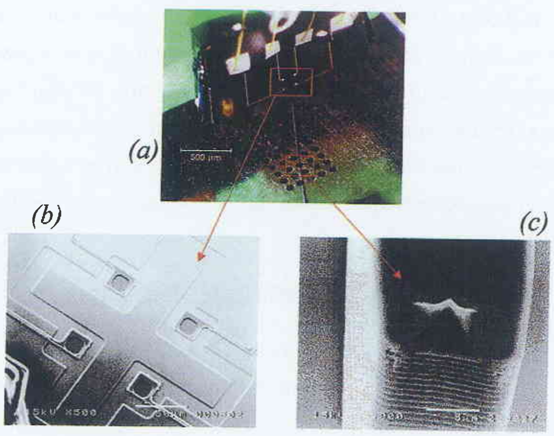

Fig. 3 a) Silicon micro-probe with b) integrated piezoresistive type force sensor and c) vertical tip.

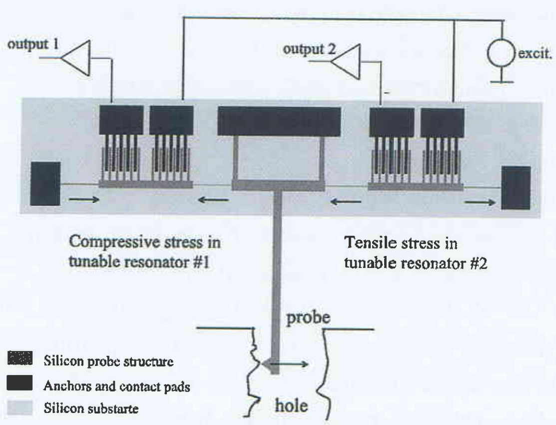

Fig. 4 Structure and operation principle.

3. FABRICATION

The fabrication process flow of the resonant-type probe is schematically depicted in Fig. 5. We use a 100-mm silicon-on-insulator (SOI) wafer with a 20.5μm thick n-doped silicon upper layer, a 0.45μm-thick silicon dioxide (SiO_2) intermediate layer, and a 525μm thick base wafer as initial substrate. A 0.8 (m-thick thermal oxide is grown on both sides of the wafer. The topside is patterned by lithography to define the resonators and the cantilever structures. Then the oxide is etched in BHF. Next, the backside silicon dioxide layer is patterned using double-side alignment lithography and etched in BHF (Fig. 5. a).

Deep etching by ICP-RIE is then performed from the backside. During this process, the front side is protected by a photoresist. Then the front side is also etched by ICP-RIE (Fig. 5. b). The oxide sacrificial layer is finally etched in HF using the supercritical carbon dioxide drying technique in order to avoid sticking of the free structures with the substrate (Fig. 5. c). Fig. 6 shows a scanning electron microscope (SEM) picture of a 1mm-long cantilever. Its cross section is 10x20.5μm. The inset shows a close-up view of the tip.

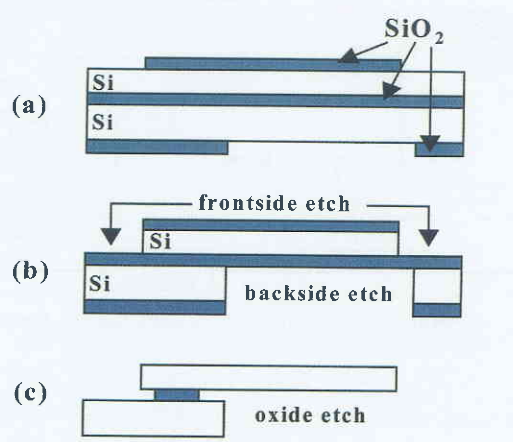

Fig. 5 Microfabrication process sequence for the resonant type probes.

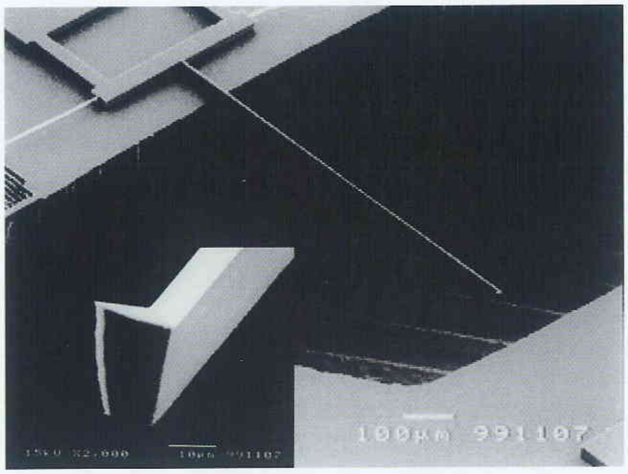

Fig. 6　Picture showing the cantilever-probe and associated tip (zoom view in the inset).

4. MODELING

4.1 First-order analytical model

When considering transversal vibrations of mechanical structures submitted to axial stress, the first resonance frequency fR have the following dependence on stress [2]:

$$f_R = f_{R0}\sqrt{\left|1-\sigma/\sigma_0\right|} \quad \cdots\cdots (1)$$

where σ is the applied stress and σ_0 the buckling threshold stress for bending. f_{R0} is the resonance frequency of the unstressed structure. For clamped-clamped cantilevers, f_{R0} and σ_0 are given by the following formulae [3]:

$$f_{R0} = 6.47\,\frac{w_2}{l_2^2}\sqrt{\frac{E}{\rho}} \quad \cdots\cdots (2)$$

$$\sigma_0 = \frac{\pi_2 E w_2^2}{3 l_2^2} \quad \cdots\cdots (3)$$

In our case, w_2, and l_2, are the width and length of the resonator bridges respectively.

With simplifying assumptions on boundary conditions on points A, B and C (see Fig. 7), one can consider the probe as a clamped-free cantilever and the resonators as clamped-clamped cantilevers. Then, an approximated analytical formula can be obtained for the resonance frequency of the deformed structure:

$$f_R = f_{R0}\sqrt{1 \pm (3/8\pi^2)(w_1/w_2)^3(l_2^2/l_1^3)Y} \quad \cdots\cdots (4)$$

w_1, and l_1 , are the width and length of the probe-cantilever. Y is the deflection at the end of the probe, which is representative of the surface profile.

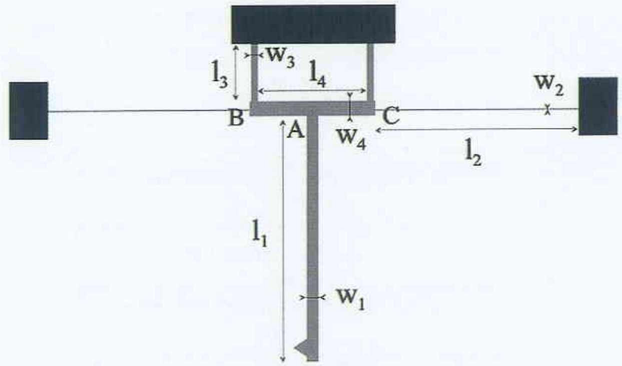

Fig. 7　Main geometrical parameters of the mechanical structure.

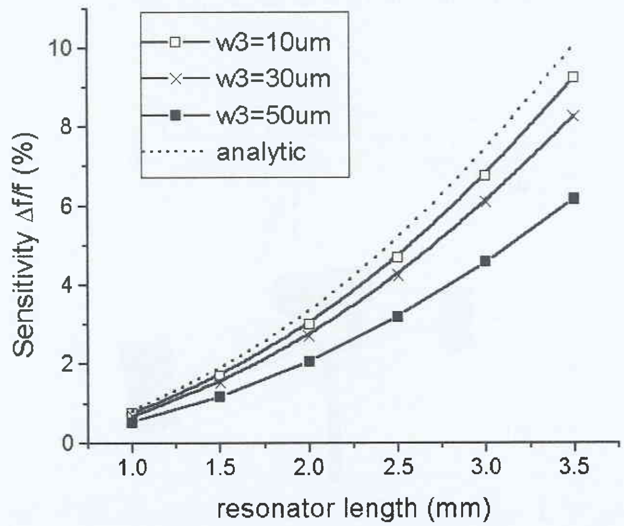

Fig. 8　Sensitivity vs. resonator length (l_2). Comparison between analytical model and FEM calculations (for different values of w_3) reveals non-negligible mismatch. In this case, $l_1 = l_3 = l_4 = 1000$, $w_1 = 30$, $w_2 = 5$ and $w_4 = 50\mu m$.

4.2 FEM modeling and optimization

Since equation (4) is based on simplifying assumptions, it can lead to non-negligible mismatch with real values, depending on the overall geometry. In particular, the dimensions l_3, l_4, w_3 and w_4, (Fig. 7) which are not taken into account in equation (4), may play an important role in some situations. This is illustrated in Fig. 8, in which we have made a comparison with data obtained from FEM calculations. It appears that different values of w_3 can lead to an error up to 30%.

Otherwise, we need for practical reasons a long cantilever probe, so that deep holes can be measured. But the smallest cantilevers have the best sensitivities, since the measurement principle is based on stress detection at the clamping point of the cantilever. The best compromise can be found through multiple,

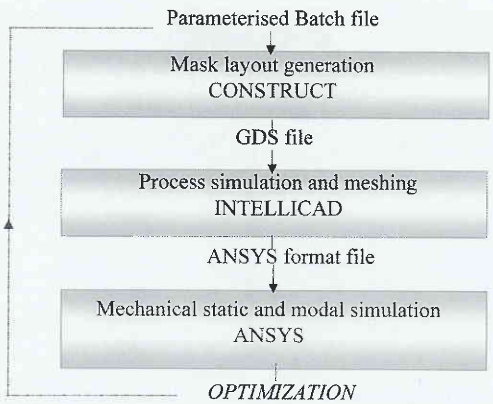

Fig. 9 Simulation flow for device optimization.

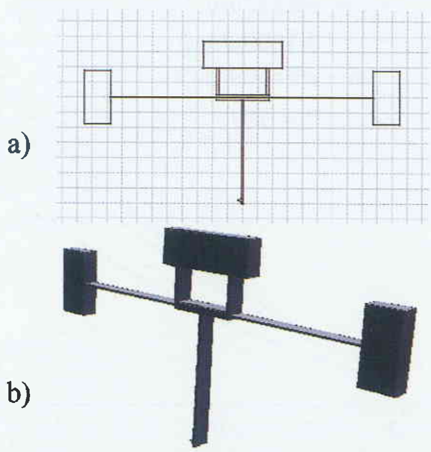

Fig. 10 a) mask layout obtained from CONSTRUCT and b) 3 D geometrical model obtained in INTELLICAD.

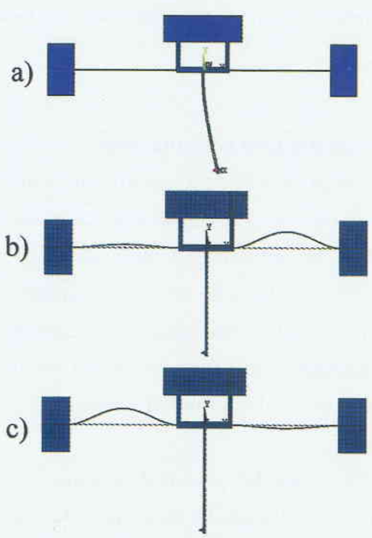

Fig. 11 Simulation results in ANSYS a) static probe deflection and b−c) are the corresponding two first mode shapes accounting for the stress effect.

systematic and iterative simulations. For fast optimization, we have used the simulation flow shown in Fig. 9.

We start with a parameterized layout generation using a program file in the CONSTRUCT software. Then a GDS file is generated and transferred as an input in the INTELLICAD software for process simulation (Fig. 10. a). The resulting 3D geometrical model (Fig. 10. b) is then converted in ANSYS format for the final mechanical simulation. The latter consists of a static deflection analysis followed by a modal analysis of the pre-stressed structure (Fig. 11).

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