Capacitive Micromachined Ultrasonic Transducer Based Integrated Actuator for Atomic Force Microscope Cantilevers

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Abstract — **The Atomic force microscope (AFM) is a versatile tool for imaging and modifying surfaces on atomic scales. The core of the device is a cantilever beam with a sharp tip. The cantilever usually measures a few hundred microns in length and tens of microns in width. Many imaging or surface modification applications require actuation of this micron scale beam. In this paper, a novel actuation mechanism is introduced. The method uses radiation pressure generated by capacitive micromachined ultrasonic transducers (cMUT). The cMUTs are fabricated on top of the cantilever beams and they operate in the megahertz range generating a DC radiation pressure in the immersion medium such as water or air. The integrated cMUT cantilever system compares favorably with piezoelectric film activated and with non-integrated ultrasonic actuation schemes. The cMUT cantilever does not require any alignment of the actuator to the cantilever. Moreover, it works in air as well as in water and is readily used with parallel cantilever probes. Finally, it is an IC compatible technology solution.**

I. INTRODUCTION

The atomic force microscope (AFM) was introduced in 1986 [1]. Since its introduction, the AFM has turned out to be a versatile tool for surface imaging and modification on atomic scales. In the simplest form of an AFM device, the cantilever is attached to the one end of a long piezoelectric tube. Applying voltages to the electrodes of the tube moves the cantilever. With this configuration the cantilever is scanned in the sample plane (x-y) as well as in the vertical (z) direction. For many applications, relative vertical motion, between the sample and the cantilever, is required to keep the cantilever deflection constant. This ensures a constant force between the cantilever tip and the sample, which is important especially with soft samples.

The dimensions of the piezoelectric tube are much larger than are those of the cantilever. Therefore the resonance frequency of the tube is usually less than 1 kHz. The maximum speed by which the cantilever can be moved is determined by this low resonance frequency, thus limiting the throughput of the device. Moreover, this configuration is not suitable for array operation, due to its size.

One possible solution to overcome the aforementioned problems is to integrate the z-actuator on top of a cantilever. Several groups have deposited piezoelectric films onto cantilevers [2]-[5]. The problem with this method is that piezoelectric films are not compatible with IC manufacturing techniques. Moreover, obtaining high quality films is usually difficult. Furthermore, operating cantilevers in liquid environment requires passivation of the piezoelectric films thus adding complexity to the fabrication process.

Another method for cantilever actuation uses the radiation pressure generated by an external transducer [6]. In this method a focused ultrasonic beam is centered onto the cantilever in a liquid environment. The generated DC radiation pressure [7] pushes the cantilever away from the source. However, this actuation method is at a disadvantage in air based tests due to significant acoustic losses in air at high frequencies.

Both the alignment problem and the absorption problem can be solved if the actuator is integrated with the cantilever. In this work, the DC radiation pressure generated by a transducer integrated with the cantilever is used for actuation. Capacitive micromachined ultrasonic transducers (cMUTs) have been developed for medical imaging. They can compete with piezoelectric transducers in terms of bandwidth and efficiency. CMUTs can generate ultrasonic pressures much higher than what can be obtained using a piezoelectric transducer for a given voltage. This makes cMUTs a good choice for cantilever actuation. A cMUT fabricated on top of a cantilever generates ultrasonic radiation into the immersion fluid (liquid or air). The RF field creates a second order DC force applied to the transducer and therefore to the cantilever. This force bends the cantilever.

II. THEORY

According to ultrasound theory an ultrasonic source operating in its nonlinear regime generates acoustic streaming into the fluid surrounding it. This streaming acts on the fluid with an, on average, constant force [8]. The reactive force induces a thrust into the transducer. This thrust can be used for actuation if the transducer is

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integrated e.g. with a silicon cantilever. The acoustic force, F, generated by a piston source driven nonlinearly is [8]

$$F = \left(\frac{8\pi}{3}\right)\left(\frac{f\,p_o}{\rho_o^2}\right)^2\left(\frac{\mu A}{c^5}\right);\, p_o = \rho_o\, c_o u_o, \quad (1)$$

where u_o is the displacement of the piston and f is the frequency of oscillation. Moreover, c_o is the sound velocity, ρ_o is the density and μ is the dynamic viscosity of the surrounding medium. A is the active area of the transducer. In the derivation of these results it is assumed that the transducer transmits plane waves in a narrow beam into dry air.

Classical continuum mechanic theory describing cantilevers during bending or torsional stress guides the design of the cantilever. A cantilever made from homogeneous silicon with a constant rectangular cross section is designed. Figure 1 shows the definitions of the magnitudes in the bending theory. The length of the cantilever is l, while w is the width and t is the thickness of the cantilever. Moreover, q, is the center of the actuating force and F is the sum of the magnitude of the acoustic force and the gravity acting on the integrated transducer-cantilever. The maximum tip deflection is [9],

$$y_{\max} = -\frac{Fl^3}{3EI};\, I = \frac{wt^3}{12}, \quad (2)$$

where E is the Young modulus for silicon, $1.3*10^{11}$ N/m^2. Here it is assumed that the cantilever is straight with uniform cross section of homogeneous material, that its base is fixed, and that no torsion occurs.

The lowest resonance frequency of the cantilever is [9]

$$f_1 = \frac{1.732}{2\pi}\sqrt{\frac{EIg}{Fl^3}}, \quad (3)$$

where g is the gravity constant 9.81 m/s^2. The maximum torsional deflection is [9]

$$\theta_{\max} = \frac{Fwl}{2Kg}, \quad (4)$$

where

$$K = qb^3\left[\frac{16}{3} - 3.36\frac{b}{q}\left(1 - \frac{b^4}{12q^4}\right)\right];\, q = \frac{w}{2}, b = \frac{t}{2} \quad (5)$$

This derivation assumes in addition to the assumptions made deriving (2) that the cantilever is loaded by equal opposing forces.

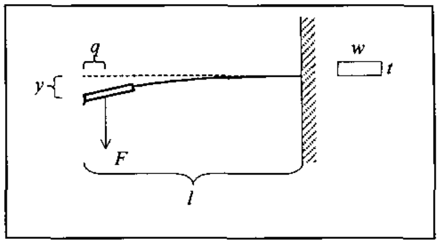

Fig. 1. The magnitudes associated with the theory of bending and twisting a cantilever.

It is evident that two factors are important with respect to design: 1) the aspect ratio of the cantilever (l/t) and 2) the frequency-pressure factor (fp_o) of the source. The aspect ratio can not be increased indefinitely due to fabrication constraints.

The output pressure of a cMUT cell is the acoustic impedance of the membrane times the velocity of the membrane. The total output power is the number of cells times the output pressure of a single cell.

II. DESIGN AND FABRICATION

We want to design a device that has a resonance frequency higher than the 10 kHz usually encountered with PZT actuated AFM devices. The reason is that, the higher the resonance frequency of the device, the broader is the flat sub-resonance band where the cantilever can be actuated. Moreover, we want a deflection of 1-2 μm in order to be able to use large excitation amplitudes when the cantilever tip is used as a point source. We also want to be able to twist the tip at least 20° to each side in order to have a shear wave source.

A. Device design

Device design was based on the theory for nonlinear acoustic force generation and the theory of bending of cantilevers described in the theory section. Simulation procedures described in [10] were used to determine cMUT specifications when a certain resonance frequency by the cMUT was desired.

Initial analysis of the cMUT-cantilever structure indicated that cMUTs working at frequencies ranging from 2 MHz to 50 MHz should be considered. Fig. 2 shows the results from simulations with 100x100μm devices operating in air, for the five membrane types to be fabricated. The devices are excitated by a 16 V AC signal and a 40 V DC bias is applied. In the plot 180 dB re µPa/V corresponds to 1 kPa/V. Table 1 summarizes the design parameters for these cMUT devices.

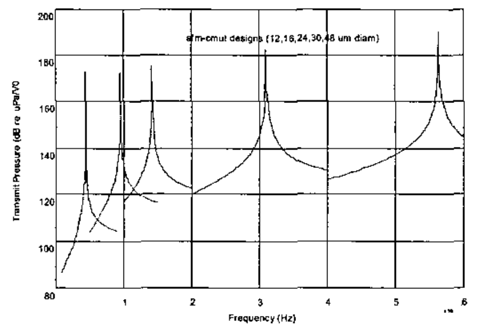

Fig. 2.The simulated output, into air, of five cMUT devices to be integrated with the AFM cantilever. The simulation is for 100x100 µm devices. The membranes are excitated with 16V AC.

Device	a(um)	#Trans	VDC(V)	ta(um)	tn(um)	Insul(um)	sigma(Mpa)
A	48	4	50	0.3	0.6	0.15	100
B	30	9	50	0.15	0.6	0.15	100
C	24	16	50	0.1	0.6	0.15	100
D	16	25	100	0.1	0.6	0.15	100
E	12	36	150	0.1	0.6	0.15	100

Table 1. The simulation parameters used with the five fabricated devices. #Trans is the number of membranes in the 100x100 µm device. Insul is the insulation thickness, sigma is the residual stress in the membrane.

Based on the mechanical theory and common design rules for cantilevers it was decided that the AFM cantilevers should have lengths in the range of 100-2000 µm and widths between 50 µm and 200 µm. Their thickness should be 5 µm to 20 µm. The spring constant of the cantilevers should range from 0.1 to 10 Nt/m.

It was also decided to fabricate T-shaped cantilevers for torsional actuation. Fig. 3 shows the schematic drawing of the device geometry. Tables 2 and 3 summarize the expected resonance frequencies, maximum tip declinations and maximum twist-angles for some of the design configurations to be fabricated. Table 2 is obtained for a 10 kPa acoustic pressure which can be obtained with the cMUT used when a 2V AC signal is applied [11].

In table 3 the calculated response of a 5 µm thick cantilever under influence of a 0.78 mN acoustic thrust is presented. The upper group is for a 100 µm wide straight cantilever and the lower group is for a 200 µm wide straight cantilever. I is 1.04E-21 m^4 and K is 1.01E-26 m^4 for the 100 µm cantilever and 2.08E-21 and 2.05E-26 respectively for the 200 µm cantilever. It is assumed that 50% of the source weight (100x100x500 µm Si) is placed at the tip. The total load of the cantilever is in practice the same as the acoustic thrust.

Using these design parameters it should be possible to obtain measurable cantilever displacements on the micron scale. In addition, by modulating the applied RF field it is possible to excite resonances of the cantilevers. The dynamic response of the cantilever can be measured with a laser vibrometer.

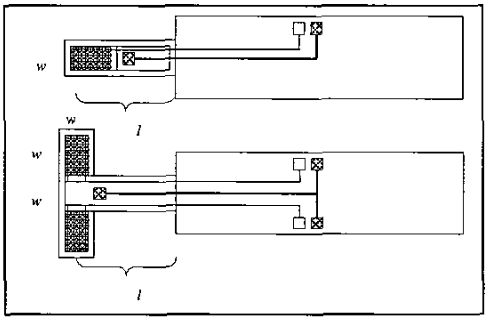

Fig. 3. The straight and the T-shaped cMUT actuated cantilever designs. The cantilevers have the same length, *l*.

Device	Area(m2)	freq(MHz)	Thrust_rad(mN)	Thrust_stream(mN)
	1.6E-09	2.5	4.81E-04	1.65E-05
40x40	1.6E-09	10	4.81E-04	2.64E-04
	1.6E-09	30	4.81E-04	2.38E-03
	1.6E-09	50	4.81E-04	6.61E-03
	1.00E-08	2.5	3.00E-03	1.03E-04
100x100	1.00E-08	10	3.00E-03	1.65E-03
	1.00E-08	30	3.00E-03	1.49E-02
	1.00E-08	50	3.00E-03	4.13E-02
100x500	5.00E-08	2.5	1.50E-02	5.17E-04
	5.00E-08	10	1.50E-02	8.27E-03
	5.00E-08	30	1.50E-02	7.44E-02
	5.00E-08	50	1.50E-02	2.07E-01
	1.0E-07	2.5	3.00E-02	1.03E-03
200x500	1.0E-07	10	3.00E-02	1.65E-02
	1.0E-07	30	3.00E-02	1.49E-01
	1.0E-07	50	3.00E-02	4.13E-01
	2.0E-07	2.5	6.01E-02	2.07E-03
200x1000	2.0E-07	10	6.01E-02	3.31E-02
	2.0E-07	30	6.01E-02	2.98E-01
	2.0E-07	50	6.01E-02	8.27E-01

Table 2. Design parameters for the cantilevers. The applied pressure is 10 kPa.

length(um)	static load(N)	acoustic thrust(N)	Torque(Nm)	y_max(m)_dyn	y_max(m)_stat	f_1(Hz)	Twist(deg)
200	1.14E-09	7.8E-04	3.90E-08	1.11E-05	1.70E-11	121.0	55
500	2.86E-09	7.8E-04	3.90E-08	1.73E-04	6.46E-10	19.6	139
800	4.57E-09	7.8E-04	3.90E-08	7.10E-04	4.21E-09	7.7	222
1100	6.29E-09	7.8E-04	3.90E-08	1.85E-03	1.50E-08	4.1	305
200	2.29E-09	7.8E-04	7.80E-08	5.55E-06	1.66E-11	122.3	109
500	5.71E-09	7.8E-04	7.80E-08	8.67E-05	6.40E-10	19.7	273
800	9.14E-09	7.8E-04	7.80E-08	3.55E-04	4.18E-09	7.7	436
1100	1.26E-08	7.8E-04	7.80E-08	9.23E-04	1.49E-08	4.1	600

Table 3. Simulation results for a 5 µm thick cantilever under influence of a 0.78 mN acoustic thrust. The upper group is for a 100 µm wide cantilever and the lower group is for a 200 µm wide cantilever.

B. Mask and Process design

By combining the standard process flows for cMUT fabrication [12] and cantilever fabrication [5] it was possible to use a modular design approach. The new process flow is obtained by concatenating the two aforementioned process flows. The fully IC compatible fabrication process contains the following major steps.

A 4-in n-type (100) silicon wafer is heavily doped in a 4-h phosphorous gas phase drive –in at 1000 °C to achieve good conductivity at the wafer surface. A thin layer of low-pressure chemical vapor deposition (LPCVD) nitride is then deposited at 800°C as an etch stop in the potassium and hydroxide water (KOH) sacrificial etching to be performed later. Amorphous silicon is subsequently deposited at 560°C to form a sacrificial layer. The deposited amporhous silicon is dry-etch patterned into hexagonally shaped islands to define the active transducer regions.

A second layer of nitride is then deposited by LPCVD at 800°C to form a thin membrane. The silane and ammonium ratio is controlled in such a way that a residual stress of 100 MPa is obtained. Vias are dry etched to allow sacrificial etching in KOH at 75°C followed by vacuum sealing with nitride deposition. Finally aluminum is sputtered and wet-etch patterned to act as the top electrode (50% membrane coverage). The same aluminum deposition also defines the bonding contacts to the bottom electrode through a lithographically defined trench in the silicon bulk. Finally the cantilevers are defined by a lithography step and by dry etching the silicon on the backside of the cantilevers.

III. EXPERIMENTS

Before testing the cMUT integrated cantilevers we measured the force generated by the cMUTs. A 2300 µg cMUT with an active area of 4,9 mm^2 featuring 1032 membranes with a 43% metallization, all 0.08 mm^2 by area, 1.15 µm by membrane thickness, 0.2 µm by insulation thickness and 0.8 µm by gap height was used to test the ability to generate acoustic thrust. We measured the radiation pressure generated by the cMUT operating at 1.76 MHz into air with a digital scale. The increase in apparent weight of the transducer corresponds to the acoustic force generated by the transducer at constant DC bias (40V). Fig 4 shows the generated thrust as a function of applied AC amplitude. The tip of a (500x100x5 µm) Si cantilever deflects 170 µm when acted on by a 0.78 mN force.

IV. DISCUSSION AND CONCLUSION

By modulating the excitation of the broadband transducer should be possible drive the cantilever at a wide frequency range. It should also be possible to shape the response of the cantilever.

Active deflection of the AFM cantilever could be used for generating longitudinal acoustic waves into a sample. If two cMUTs are operated side by side torsional modes could be introduced into the cantilever. This allows shear waves to be introduced into the probed sample.

We have used the DC radiation pressure generated by a cMUT to actuate an integrated cMUT cantilever system. The cMUT fabricated on top of the cantilever generates ultrasonic radiation into the immersion fluid (liquid or air). The RF field creates a second order DC force applied to the transducer and therefore to the cantilever. This force bends the cantilever. Being able to perform active control of both amplitude and frequency of an AFM cantilever could open up new possibilities for nano-scale nondestructive testing of e.g. bio-samples.

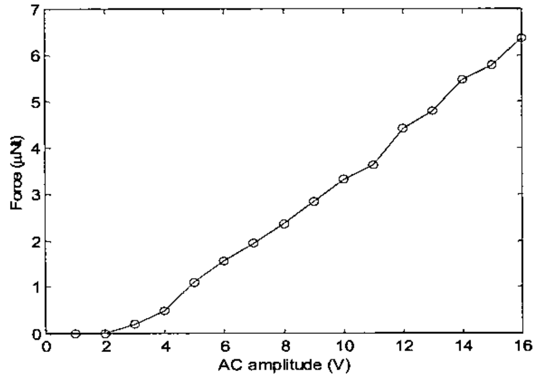

Fig. 4. Force generated by an 100x100 µm transducer in air.

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