Development of Surface-micro-machined Binary Logic Gate for Low Frequency Signal Processing in MEMS based Sensor Applications

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ABSTRACT

This paper presents the development of surface micro-machined digital gates for MEMS based digital logic implementation. They are specifically designed for fabrication along with a MEMS sensor in the same process flow on the same wafer. The micro-cantilever switch, which is the fundamental building block of the devices, has been optimized with analytical method and finite element method based simulation. In this work, as fundamental building blocks, digital inverter and universal gates have been developed. Three different specifications on the operating voltage have been adopted and accordingly three variants of devices have been developed. The structures have been fabricated using standard surface micro-machining process. They have also been characterized for their mechanical spectral response under forced vibration.

Keywords: MEMS, surface micro-machining, PolyMUMPs, cantilever, electrostatic actuation.

1 INTRODUCTION

MEMS sensors are widely used in many domains of slow signal transducing applications. The sensor output is generally interfaced and finally digitized in preferred format for further processing and transmission. The most common practice in such sensor interfacing and signal processing activities is utilizing CMOS circuits and combining MEMS process with it or connect the CMOS circuit with the MEMS sensor block in the same package. Although hybrid and even monolithic integration of MEMS with CMOS blocks are available, it asks for increased fabrication cost and customization of the process and packaging techniques. Therefore, if digital logic can be implemented in MEMS process itself, these complexities can be avoided and a complete monolithic MEMS based sensor system can be realized in the same process. Apart from that, MEMS devices, in general, are very low power consuming, very high isolation and very low leakage issues [1]. They are also not as sensitive to ionization radiation as semiconductor devices [2]. These are among the topical challenges in CMOS technology where MEMS devices can provide better characteristics.

This paper presents a concise depiction of the development of binary logic gates using surface micro-machining technology aiming at complete monolithic MEMS based sensor system. In [2,3,4] the operating principle of such micromechanical logic inverters have been presented. In [3,4] the detailed design methodology and theoretical dynamic performance evaluation of the inverter had been produced. The inverter was designed using PolyMUMPsPlus [5] surface micromachining technology. In [6] the principle of operation of the inverter was extended to design and fabricate universal gates using PolyMUMPs [7] process. Three different variants of devices of same functionality had been designed and fabricated based on three different operating voltage specifications. It has also been shown that simply by interchanging the power supply and ground connections the same universal gate circuit can be used as NAND as well as NOR gates [6,8].

In this paper further work on the development of the inverter and universal gates of these types using PolyMUMPs process have been furnished. Since the design methodology and fabrication details have already been discussed in [6], apart from discussing the operating principle in brief, this paper mainly confers the vibration characterization of the beams. The beams have been excited for out-of plane vibration and their resonance frequency and resonant mode shapes have been recorded using Laser Doppler Vibrometer for verifying the feasibility of the design dimensions in terms of stiction and release.

The paper is constructed as follows. In the next chapter the operating principle of the inverter and the universal gate have been presented. The design approach and the fabrication details have been briefed in the succeeding chapters. The vibration characterization of the devices has been detailed in the section 5 and finally the conclusions have been drawn in the section 6.

2 OPERATING PRINCIPLE

The proposed micro-electro-mechanical logic gate inverter works on the principle of electrostatic actuation of cantilever beams. Figure 1 shows a cantilever beam with a pull-down electrode. The beam can be actuated or pulled down by applying voltage between the beam and the bottom electrode. If the beam is allowed to bend and get contact with the output pad, electrical contact can be achieved between the beam and the output pad [3,4,6].

If V_{ON} is the required voltage for the cantilever to get such contact, table 1 gives the truth table satisfied by the beam. The first two rows of the table reproduce the conditions of nMOS transistor and the lower half of the table simulates the condition of pMOS transistor in CMOS configuration [3,4,5].

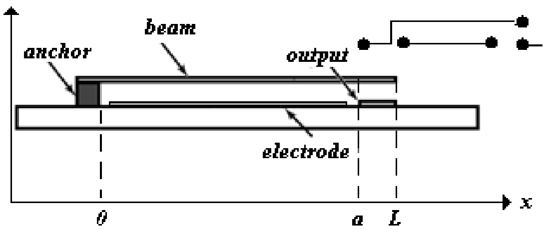

Figure 1: Schematic of the cantilever switch.

When two such cantilevers are connected as shown in figure 2 it can be shown [3,4] that the circuit satisfies the truth table of a binary inverter. Similarly when four beams are connected as shown in figure 3, the circuit behaves as a universal gate [6].

Voltage at the beam	**Voltage at the electrode**	**Voltage between beam and electrode**	**Output condition**
0	0	0	High impedance
0	V_{ON}	V_{ON}	0
V_{ON}	0	V_{ON}	V_{ON}
V_{ON}	V_{ON}	0	High impedance

Table 1: Truth table of the cantilever switch.

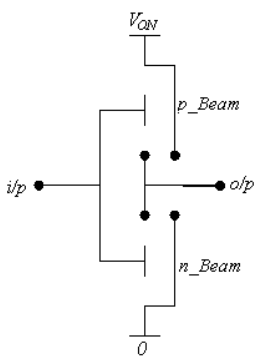

Figure 2: Schematic of the MEMS based digital inverter.

3 DESIGN APPROACH

The devices have been designed using PolyMUMPs surface micro-machining process in CoventorWare platform [10]. Three operating voltages for the three variants have been chosen as furnished in table 2. The CoSolveEM module [10] has been used, along to finalize the beam lengths required for achieving pull-in voltages [6] as specified. The beam width has been optimized for critically damped or overdamped dynamic behavior of the beams under forced vibration [6]. The natural frequency of vibration of the beams has been obtained from MemMech simulation in CoventorWare platform. The detailed design approach has been already reported in [6]. In table 2 the final dimensions and performance parameters of the beams have been furnished as a summary of the results reported in [6].

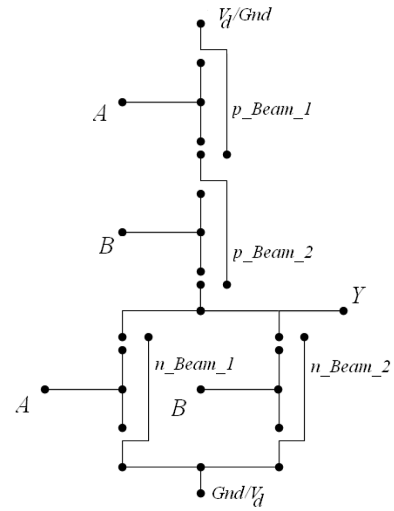

Figure 3: Schematic of the MEMS based universal gate (NAND/NOR).

Variant	Type 1	Type 2	Type 3
Operating voltage, V_{ON}	5.0 volt	3.3 volt	1.0 volt
Beam length, *L*	400 µm	170 µm	340 µm
Beam width, *b*	10 µm	10 µm	10 µm
Beam thickness, *h*	2 µm	1.5 µm	1.5 µm
Beam in layer	*Poly1*	*Poly2*	*Poly2*
Bottom electrode layer	*Poly0*	*Poly1*	*Poly1*
Air gap, y_0	2 µm	0.75 µm	0.75 µm
Dimple	0.75 µm	No	No
Maximum deflection	1.25 µm	0.75 µm	0.75 µm
Natural frequency, f_0	17.1 kHz	71.5 kHz	18.3 kHz

Table 2: Design specifications and properties of three variants of inverter and universal gate.

4 FABRICATION

Total 30 samples of each device have been fabricated using PolyMUMPs process [6,7]. A brief account of the fabrication details have been given in [6]. The description of the layers and the corresponding thicknesses are also furnished in table 2. Scanning Electron micrographs of a few of the fabricated devices have been shown in figure 4 and figure 5.

5 VIBRATION CHARACTERIZATION

All the devices have been thoroughly characterized for their mechanical dynamic response using Laser Doppler Vibrometer (LDV). Figure 6 shows the LDV set-up used in characterizing the devices. It is a Polytec made LDV with MSA 400 Micro-motion Analyser, OFV 511 Laser Interferometer and OFV 3001 Vibrometer Controller [11,12].

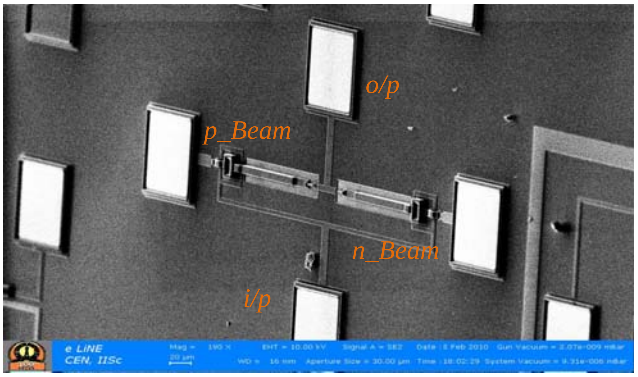

Figure 4: Micrograph of 3.3 volt inverter

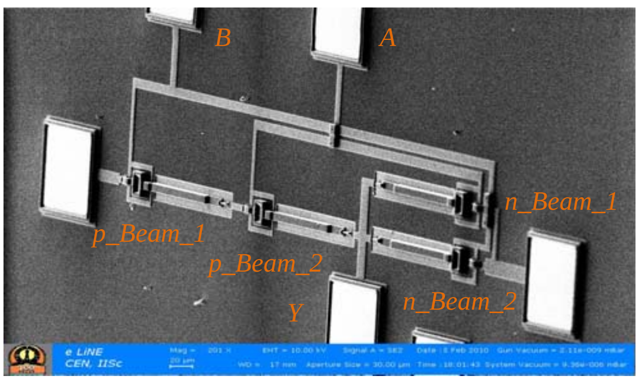

Figure 5: Micrograph of 3.3 volt universal gate

Figure 6: Photograph of the LDV set-up

In the experiment, we apply a sinusoidal voltage of small amplitude 100 mV between the beam and the bottom electrode and the frequency of the signal is swept from 0 to 1 MHz to excite resonance in the beams. The amplitude of the signal is kept much smaller than the pull-in voltage of the beams in order to eliminate spring softening [12] in the beams. Wafer prober is used in order to provide the signal to the pads on the wafer. Each beam in the arrays has been scanned repeatedly and their vibration velocity spectrum has been recorder in LDV. The resonance peaks have been noted from the spectrums and the generated mode shapes have been observed.

Figure 7 shows the fundamental mode shape of one of the beams in the 3.3 volt version of the MEMS inverter as obtained from LDV measurement. It also shows that the vibration displacement spectrum as produced by the LDV.

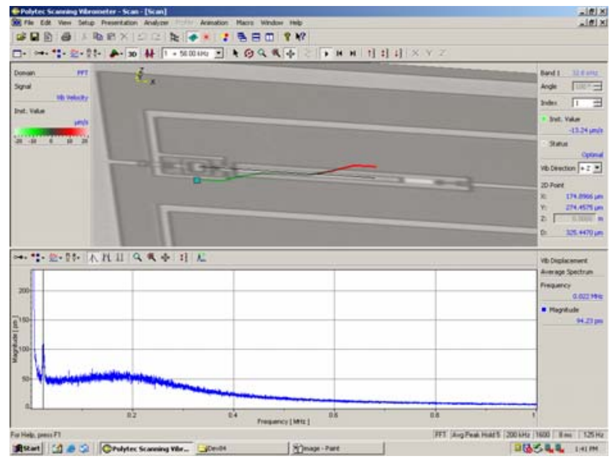

Figure 7: Fundamental mode shape and vibration spectrum of the beams in 3.3 volt MEMS inverter

It is imperative to mention here, that, although the beams in the 3.3 volt version of the digital devices have been designed aiming over-damped dynamic response, the fabricated beams show under-damped response. They show a resonance at 32.6 kHz which is much below their un-damped natural frequency 71.5 kHz, but an over-damped beam should not resonate while forced to vibrate. One legitimate answer to this can be inadequacy of the squeezed film damping model that is used in determining the width of the beams [6]. Similar results and similar justification can be given to the results for the other versions of beams, too.

It has been observed from the mode shape of the three versions of beams that in the 1.0 volt version devices the beams are stuck to bottom at the end whereas the other two versions of the beams are free and vibrate properly. Figure 8 shows the shape of the beam reproduced by the LDV under forced sinusoidal excitation.

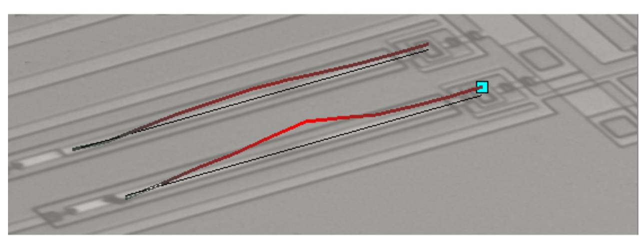

Figure 8: Fundamental mode shape and vibration spectrum of the beams in 1.0 volt MEMS universal gate showing that the beam ends are stuck to the output pad

It may be noted that the beams in 1.0 volt version of the digital circuit have the least stiffness among the three versions. They have a thickness of 1.5 µm and length 340 µm. Since the stiffness constant is proportional to the cubic power of the ratio of thickness and length, they have much lower value of stiffness compared to the other two versions. Therefore these beams are more susceptible to stiction forces during release as well as during operation.

6 CONCLUSIONS

In this work, mechanical characterization of the MEMS based digital blocks have been presented. The three versions of the gates were designed and fabricated using PolyMUMPs surface micro-machining process. The devices have been characterized for their dynamic mechanical response using Laser Doppler Vibrometer. It has been observed from the mode shape of vibration of the beams that the design of the beams in the 1.0 volt version is not viable from the point of view of fabrication of the devices. They are highly vulnerable to permanent stiction issues unlike the other two designs. Therefore all functional characterization of the digital devices can be performed only on the two other versions of the design.

It has also been observed that the devices have shown resonance in their dynamic response, although the beams were designed either for critically damped or over-damped dynamic. Though the resonance frequency is much lower than the natural frequency of the beams due to ambient damping, it still produces significant amplitude at resonance and therefore it can produce considerable transient vibration when the digital input changes from state '0' to state '1' or vice versa. This is undesirable for performance of the devices.

In this work, only the preliminary mechanical characterization of the devices has been reported. These tests are important particularly for having an idea about the condition of the beams before actual functional operation. Detailed functional characterization of the beams is currently being performed and will be reported soon.

ACKNOWLEDGEMENT

The authors would like to thank National Program on Micro and Smart Systems (NPMASS), Govt. if India, for enhancing the MEMS design and simulation support at MEMS Design Lab, Advanced Technology Development Centre (ATDC), IIT Kharagpur and for infrastructure development which supported the fabrication of the devices. The authors would also like to thank Prof. Rudra Pratap and his group members at Indian Institute of Science, Bangalore for allowing and assisting us in characterizing our devices using their LDV set-up.

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