Sensors and Actuators, A21–A23 (1990) 328–331

Electrostatic-comb Drive of Lateral Polysilicon Resonators

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Abstract

This paper investigates the electrostatic drive and sense of polysilicon resonators parallel to the substrate, using an interdigitated capacitor (electrostatic comb) Three experimental methods are used microscopic observation with continuous or stroboscopic illumination, capacitive sensing using an amplitude-modulation technique and SEM observation The intrinsic quality factor of the phosphorus-doped low-pressure chemical-vapor-deposited (LPCVD) polysilicon resonators is $49\,000 \pm 2000$, whereas at atmospheric pressure, $Q < 100$ The finger gap is found to have a more pronounced effect on comb characteristics than finger width or length, as expected from simple theory

1. Introduction

Mechanical resonators are highly sensitive probes for physical or chemical parameters which alter their potential or kinetic energy [1] Silicon resonant microsensors for measurement of pressure [2], acceleration [3], and vapor concentration [4] have been demonstrated Recently, polysilicon micromechanical structures have been resonated electrostatically parallel to the plane of the substrate by means of one or more interdigitated capacitors (electrostatic combs) [5, 6] Some advantages of this approach are (i) less air damping on the structure, leading to higher quality factors, (ii) linearity of the electrostatic-comb drive and (iii) flexibility in the design of the suspension for the resonator For example, folded-beam suspensions can be fabricated without increased process complexity, which is attractive for releasing residual strain and for achieving large-amplitude vibrations [5, 6] Such structures are of particular interest for resonant microactuators [7]

This paper reports the initial characterization of the electrostatic-comb drive and additional measurements on polysilicon resonators Test structures are fabricated from a single layer of LPCVD polysilicon using a simple five-mask process [5, 6] Variations in the finger lengths, widths and gaps between fingers in the comb are incorporated into a series of test structures Observations of resonating structures under an optical microscope and a scanning electron microscope are used to measure directly the electromechanical transfer function and the quality factor of the mechanical resonance, Q Finally, the motional current in the sense capacitor is found without on-chip circuitry by means of a carrier modulation technique

2. Electrostatic-comb Drive

Figure 1 is an SEM of a linear resonant plate with two electrostatic-comb drives The circuit configuration for resonating the device is shown in Fig 2, where V_P is the drive d c bias and V_d is the a c drive voltage The derivative of the drive capacitance with respect to lateral displacement, $\partial C/\partial x$, is constant for the comb drive for displacements much less than the finger overlap Therefore, the electromechanical transfer function relating the phasor vibrational amplitude

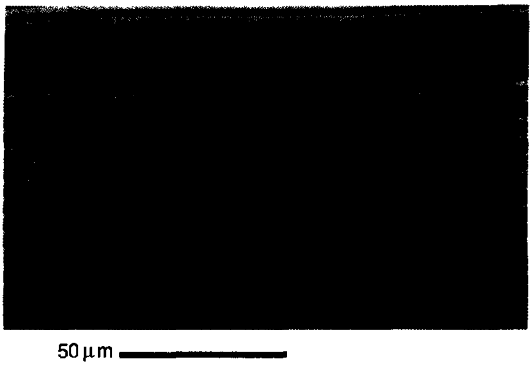

Fig 1 SEM of a linear resonant plate with two electrostatic-comb drives

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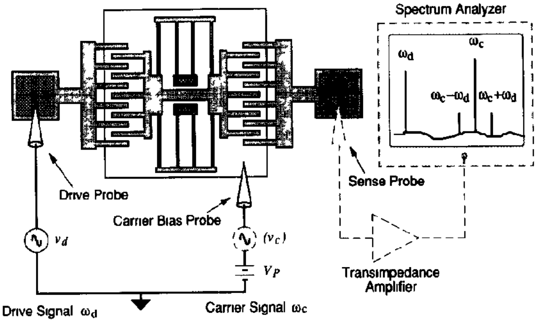

Fig 2 Circuit schematic indicating the electrical connections necessary for driving a lateral resonant microstructure into resonance The dotted lines correspond to additional circuitry required for motional current sensing via electromechanical modulation

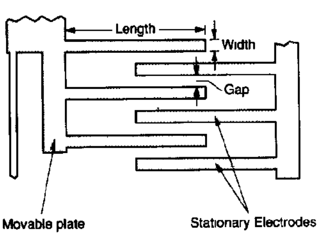

Fig 3 Comb-structure dimensions

X to the a c drive voltage V_d at resonance is given by [5, 6]

$$\left|\frac{X}{V_d}\right| = V_P \frac{Q}{k_{sys}} (\partial C/\partial x) \tag{1}$$

where Q and k_{sys} (system spring constant) are the mechanical characteristics of the resonator The transconductance of the resonant structure, defined by $G(j\omega) = I_s/V_d$, where I_s is the phasor current in the sense electrode, is given by [5, 6]

$$\left|\frac{I_s}{V_d}\right| = \omega V_P V_S \frac{Q}{k_{sys}} (\partial C/\partial x)^2 \tag{2}$$

where V_S is the bias voltage between the structure and the stationary sense electrode

In order to design the comb drive using these results, values are needed for $\partial C/\partial x$ and the quality factor Q of the resonance The derivative $\partial C/\partial x$ is a function of the finger width and length, the comb gap, the polysilicon thickness, and the offset from the substrate (Fig 3) The effects of different finger widths, lengths, and gaps are studied for the specific case of a 2 μm thick polysilicon resonator with 200 μm long folded flexures, which is suspended 2 μm above the substrate The quality factor is determined by viscous drag from Couette flow under the resonant structure [5, 6] and by damping between the comb fingers The latter contribution is evaluated using measurements on these structures

3. Technique for Characterizing Resonant Microstructures

Several techniques have been developed to characterize resonant microstructures They include visual techniques, in which vibrating plates are observed under high magnification (provided by a scanning electron microscope and optical microscopes) under continuous or stroboscopic illumination, and an electrical technique, which promises high accuracy and convenience

Visual determination of resonant frequency and quality factor requires large driving voltages in air to provide sufficient vibrational amplitudes Typical d c bias voltages V_P are 40 to 50 V, with a c drive-voltage amplitudes of about 10 V Under continuous illumination, amplitudes are estimated by observing the envelope of the vibrating structures By strobing the light source at a frequency 100 times less than that of the a c drive, the mode shape of the resonating structure can be observed

Measurement of the current induced in the interdigitated sense electrode (Fig 2) by motion of the structure is difficult without an on-chip buffer circuit [8] However, this can be accomplished by superimposing a high-frequency a c signal on top of the d c bias which is applied to the structure This signal serves as a carrier which is modulated by the time-varying sense capacitance As a result, electrical feedthrough from fixed parasitic capacitors and the sense current due to the vibrating structure are separated in the frequency domain, as shown in Fig 2

4. Experimental Results

The resonant frequencies of the set of resonators with different comb geometries are listed in Table 1 with the comb dimensions defined in Fig 3 The values obtained from both optical and electrical techniques are in close agreement The calculated resonant frequencies in Table 1 are found using Rayleigh's method [5, 6]

$$f_r = \frac{1}{2\pi}\left[\frac{2Eh(W/L)^3}{(M_p + 0\ 3714M)}\right]^{1/2} \tag{3}$$

where h, W and L are the thickness, width and length of the supporting beams, respectively, and M_p and M are the masses of the plate and the beams This equation assumes that the folded structure allows release of the residual compres-

TABLE 1 Calculated and measured resonant frequencies of a set of comb-drive structures suspended with 200 μm long beams

Comb characteristics				Resonant frequencies (kHz)			
No of fingers	Finger length (μm)	Finger width (μm)	Gap (μm)	Calculated	Measured		
					Optical ±0 05	Strobe ±0 05	Electrical ±0 05
12	20	2	2	23 4	22 9	23 1	22 8
12	30	2	2	22 6	22 3	22 4	22 9
12	40	2	2	21 9	22 1	22 0	22 0
12	50	2	2	21 3	21 5	21 6	21 6
12	40	3	2	20 4	20 9	20 5	20 3
12	40	4	2	19 1	19 2	19 3	19 3
12	40	5	2	18 1	18 8	18 4	18 0
12	40	2	3	21 3	21 1	21 2	21 4
12	40	2	4	20 8	20 5	20 7	21 0
12	40	2	5	20 2	20 0	19 9	19 8

sive strain in the polysilicon film A best-fit value for the Young's modulus for these structures is $E = 150$ GPa An earlier processing run with a similar process has a best-fit Young's modulus of 140 GPa, somewhat lower than that from the data of Table 1

Optical and electrical measurements of the quality factor Q are plotted in Fig 4 for a set of 12-finger test structures with different finger gaps The fingers are 40 μm long, with an overlap of 20 μm and 2 μm × 2 μm cross sections An important observation from Fig 3 is that Q is low for structures with either small finger gaps or widely separated fingers

By measuring the electromechanical transfer function at resonance, eqn (1) together with the calculated spring constant k_{sys} yields values of the derivative of drive capacitance with displacement Figure 5 is a plot of $\partial C/\partial x$ as a function of the finger gap, which shows the expected sharp increase with reduced gaps Figures 4 and 5 provide the empirical basis for designing electrostatic-comb drives

The resonant behavior of an 11-finger comb structure is observed at a pressure of 1×10^{-7} Torr

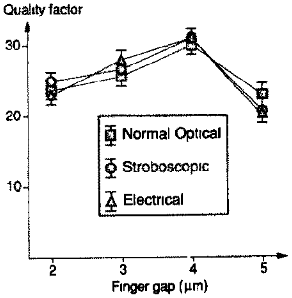

Fig 4 Plots of quality factor vs finger gap comparing optical and electrical measurement techniques

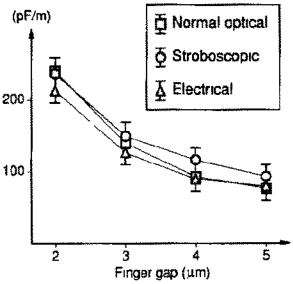

Fig 5 Plots of $\partial C/\partial x$ vs finger gap comparing results obtained via optical and electrical measurement techniques

in a scanning electron microscope Figure 6 is an SEM of the vibrating structure suspended by a pair of folded beams 140 μm long The motion of the structure is lateral to the substrate, without any indication of torsional or vertical motion It is important to note that the resonant frequency of the vertical mode is identical to that of the

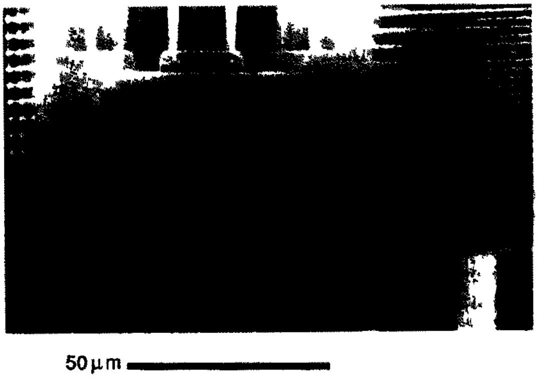

Fig 6 SEM of a vibrating microstructure showing no indication of any torsional or vertical motion under high vacuum (10^{-7} Torr)

designed lateral mode due to the square cross section of the suspensions The electrostatic comb, with underlying ground plane, is therefore capable of cleanly driving just the lateral mode of the structure Finally, the structure is observed to elevate about 200 nm upon application of the d c bias, an effect which warrants further study

In the SEM, this structure resonates at $f_r = 31\,636\,91 \pm 0\,02$ Hz for a d c bias of 5 V The quality factor is evaluated with both time domain and frequency domain methods

$$Q \simeq 1\,43 T f_r \quad \text{and} \quad Q = \frac{f_r}{f_2 - f_1}$$

where T is the time for the oscillation amplitude to drop from 90% to 10% of its full amplitude after stopping the drive and $(f_2 - f_1)$ is the -3 dB bandwidth The values of Q are $49\,000 \pm 2000$ and $50\,000 \pm 5000$ for the time and frequency domain methods, respectively The drive efficiency for this design in a vacuum is measured to be 20 ± 2 μm/V under a d c bias of 5 V

5. Conclusions

This paper has demonstrated three experimental methods for characterizing the electrostatic-comb drive of lateral polysilicon resonators Transfer function and quality-factor measurements obtained with both optical and electrical techniques agree within the estimated experimental errors Additional simulation and experimental studies are needed to fully characterize the comb drive, however, the initial results presented here provide empirical guidelines The gap between comb fingers is found to be the most important design parameter for both the quality factor and the drive efficiency for operation at atmospheric pressure

Observations of the resonator in the SEM demonstrate that the electrostatic comb is capable of selectively exciting only the lateral mode of oscillation By strobing either the electron beam or the video signal, it is hoped that the motion of the structure can be observed more precisely

Acknowledgements

The authors wish to thank D S Eddy of General Motors Research Laboratories for initiating discussion of electrostatic drive, J J Bernstein of the Charles Stark Draper Laboratory for suggesting the modulation technique, Professor R M White and T A Faltens of the University of California at Berkeley for initiating and helping with the SEM observations, and D P Schultz for the optical observations This project is funded by General Motors Research Laboratories through the Berkeley Sensor and Actuator Center

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