(Electro-) Mechanical Characteristics of Electrostatically Driven Vacuum Encapsulated Polysilicon Resonators

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Abstract— The design, fabrication and performance of vacuum-encapsulated electrostatically driven polysilicon resonating beams, 210–510 μm long, 100 μm wide, and 1.5 μm thick, are described. The shortest beams have a fundamental frequency of 324 kHz, a gauge factor of 2400 and a quality factor of 600 at cavity pressures of 0.15 mbar. Intrinsic quality factors of 18 000 were measured below 0.01 mbar.

I. INTRODUCTION

RESONANT sensors provide a frequency output. They have proven to offer the highest resolution, performance and long-term stability in the field of mechanical sensors today [1]–[4]. In order to eliminate resonant frequency shifts due to physical (e.g., mass loading, dust, vapor absorption) and chemical (e.g., corrosion) interactions of the resonator with the surroundings and further, to attain a high mechanical quality factor, the resonator must be housed in an evacuated cavity. Recent work on *local* sealing, whereby the resonator is housed inside an evacuated *micro*cavity, defines a novel trend in the future development of resonant mechanical sensors [3]–[9]. The resonator together with the surrounding shell can be considered as a *resonant strain gauge*, which replaces the more conventional piezoresistance strain gauge.

In this letter, the design, fabrication, and performance characteristics of vacuum encapsulated polysilicon resonating beams are described. The resonators are preferably operated in a one-port configuration based on electrostatic drive and detection mechanisms [10]–[13]. As opposed to earlier designs [2]–[8] this scheme does not suffer from disturbing frequency shifts due to thermally induced axial loads and can be represented by a very simple equivalent circuit. Further, it leads to a homogeneous resonator, thus eliminating built-in static moments, and to a minimum number of interconnecting wires along with a rather simple layout structure.

II. DESIGN AND FABRICATION

The basic structure of the resonator is shown in Fig. 1. The resonator is housed in an evacuated cavity and consists of a doubly supported prismatic beam with a rectangular cross section. Electrostatic excitation and detection of the vibration is employed [10]–[13]. From an electric view point, the structure defines a four-terminal device. Both the one- [11], [13] and two-port [10], [12] approach have been used for excitation and detection, as indicated by the driving schemes

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TABLE I
ELECTRICAL DRIVING SCHEMES, INDICATING THE TERMINAL VOLTAGES OF THE STRUCTURE DEPICTED IN FIG. 1, FOR BOTH A ONE-PORT AND A TWO-PORT CONFIGURATION¹

Terminal	One-port				Two-port	
	Ia	Ib	Ic	Id	IIa	IIb
1	$V_P + v(t)$	null	null	$V_P + v(t)$	gnd	$v(t)$
2	$V_P + v(t)$	$V_P + v(t)$	null	null	V_P	V_P
3	null	$V_P + v(t)$	$V_P + v(t)$	null	$v(t)$	gnd
4	gnd	$V_P + v(t)$	$V_P + v(t)$	gnd	$v(t)$	gnd

Fig. 1. Schematic cross section of a vacuum encapsulated resonator depicted as a four-terminal device. Beams varying in length from 210 μm to 510 μm , with a thickness of 1.5 μm and a width of 100 μm were fabricated. Gap spacings are approximately 1.2 μm .

in Table I. It turned out that resonators configured as a one-port according to scheme Ia gave the best results in terms of a high signal-to-noise ratio and a small influence of parasitic loads.

Surface micromachining [10] was used for fabrication. The resonators are 210–510 μm long, 100 μm wide and 1.5 μm thick, with a gap spacing of approximately 1.2 μm . The thickness of the sealing cap is approximately 2.6 μm . Fine-grained polysilicon grown by Low Pressure Chemical Vapour Deposition (LPCVD) was used as a structural material and undoped plasma enhanced chemical vapour deposited (PECVD) oxides were used as the sacrificial layer materials. The conducting areas of the capacitor plates were defined by (local) boron implantation of the silicon substrate, the polysilicon beam and the cap. The electrodes are mutually insulated through thin LPCVD silicon nitride layers. Following removal of the sacrificial layers in HF and appropriate rinsing, freeze drying from cyclohexane was used to prevent sticking of the beams to the substrate (or to the cap). A novel freeze drying procedure was developed which, as opposed to other methods [7], [8], offers enhanced speed and does not require vacuum equipment. Evacuation of the cavity was achieved

¹The "null" indicates the low voltage terminal of the impedance measurement system and "gnd" stands for ground potential. Further, V_P indicates the dc polarization voltage [10]–[13] and $v(t)$ the ac driving voltage.

Fig. 2. SEM photograph of a sealed polysilicon resonator, 310 μm long, 100 μm wide and 1.5 μm thick. The three bonding pads for electrical connection with the cap (upper), the bottom (lower) and the beam (right) are clearly visible.

through reactive sealing [14] with LPCVD silicon nitride. It is noted that the sealing material must have good insulating properties, otherwise the electric terminals labelled 1, 2 and 3 in Fig. 1 will be short circuited. A SEM photograph of a sealed polysilicon resonator is shown in Fig. 2. Details of fabrication are presented elsewhere [15].

III. ELECTROMECHANICAL CHARACTERISTICS

An admittance plot of a typical one-port resonator is shown in Fig. 3. In a narrow frequency regime around the fundamental mode, the resonator can be represented by the equivalent electric network shown in the insert of Fig. 3 [11], [13], [15]. Note that this same circuit is also used to model quartz crystals. The static capacitance C_0 is a true electrical capacitance, whereas the $R_1 L_1 C_1$ series branch represents the mechanical behaviour. In effect, the capacitance C_1 , the inductor L_1 and the resistor R_1 are due to the mechanical compliance of the resonator, the resonator mass and the mechanical losses, respectively [15]. The resonant frequency f_s is defined as the frequency whereby L_1 and C_1 form a short circuit, i.e., $f_s = 1/2\pi\sqrt{L_1 C_1}$. At this frequency, the conductance displays a maximum. More details regarding the electromechanical behaviour are presented elsewhere [15].

The effective Young's modulus and residual strain of the heavily boron-doped polysilicon layer were extracted by measuring the resonant frequencies of beams of varying length [15], yielding, $E/(1 - \nu^2) = 166$ GPa and $\varepsilon_o(1 - \nu^2) = +36.8$ ppm (tensile), where E is the Young's modulus, ν the Poisson's ratio and ε_o the residual strain. An especially designed "dual cavity structure" [15] was used to measure the mechanical quality factor as a function of the pressure inside the cavity. It was found that for all beam lengths, the quality factor is inversely proportional to the ambient pressure in the range from .01 to 1.0 mbar. The Q -factor becomes independent of pressure below 0.01 mbar, yielding values close to 18 000. By matching the Q -factor of a sealed resonator and of

Fig. 3. Measured and calculated responses, showing the conductance and the susceptance of the electrostatically driven one-port resonator for a microbridge with a length of 210 μm , a width of 100 μm , a thickness of 1.50 μm and a lower gap spacing of 1.18 μm . The interconnection is according to scheme 1a of Table I ($V_P = 6.0$ V, $v = 0.01$ V). The dashed lines indicate the response function of the depicted one-port network using the following parameter values: $C_1 = 1.4252$ pF, $L_1 = 169.64$ H, $R_1 = 582,780$ Ω and $C_0 = 0.39$ pF. This gives an extracted series resonant frequency $f_s \sim 323,682$ Hz and a quality factor $Q \approx 592$.

a dual cavity resonator, the cavity pressure was obtained. This revealed pressures in the range from 0.1–0.2 mbar, corresponding to a Q -factor of approximately 600 for the 210 μm long beam. This is in agreement with predictions of the cavity pressure based on details of the sealing process [15].

IV. APPLICATION AS RESONANT STRAIN GAUGES

A four-point bending beam deflection jig as shown in the insert of Fig. 4 was used to determine the sensitivity of the resonant frequency f_s to axially applied strain ε . Fig. 4 shows the square of the resonant frequency for two different beam lengths as a function of the applied displacement (see also figure caption). Measured gauge factors $G_\varepsilon \equiv (1/f_s)(df_s/d\varepsilon)$ [9], are 2400 and 3600 for the 210 μm and 310 μm long beams, respectively. The temperature dependence of the resonant frequency was measured by placing the wafer on a Peltier element. Measured temperature coefficients $TC \equiv (1/f_s)(df_s/dT)$, where T denotes temperature, are: -135, -202, -380 and -394 ppm/ $^\circ\text{C}$ for the 210, 310, 410, and 510 μm long beams, respectively. This turns out to be greater than the intrinsic dependence which is close to -40 ppm/ $^\circ\text{C}$ [3]. Possible explanations for this discrepancy are found in thermally induced stresses due to mismatches in the thermal expansion coefficients of the different materials (silicon, polysilicon, silicon nitride, aluminum) used. Since the longer beams have a higher gauge factor, this would also explain the increase of the temperature coefficient with increasing beam length.

V. CONCLUSION

Electrostatically driven vacuum encapsulated polysilicon resonators were successfully fabricated using surface micro-machining techniques. The resonators are preferably config-

Fig. 4. Square of the fundamental resonant frequency, of a 210 μm and 310 μm long beam, vs. the displacement applied to a four-point bending beam deflection jig shown in the insert. Based on a linear theory, the relation between the induced axial strain ϵ and the displacement δ can be expressed as: $\epsilon = \delta h_s / (La(1 + 2a/3L))$, where h_s is the thickness of the sensor beam. The dimensional parameters are: $a = 15.0$ mm, $h_s = 0.406$ mm and $L = 4.0$ mm. The solid curves represent least square fits based on second-order polynomials.

ured as a one-port. A network consisting of a capacitor in parallel with a series RLC -branch accurately represents the resonator and can be embedded in a larger circuit and analyzed with circuit simulation software such as SPICE. Reactive sealing with LPCVD silicon nitride resulted in cavity pressures (0.15 mbar) close to the deposition pressure. A typical quality factor of 600 was measured for the 210 μm long beams. Quality factors approaching 18,000, being independent of pressure, can be attained by using a more sophisticated sealing procedure, aimed at achieving sealing pressures below 0.01 mbar. A gauge factor of 2,400 and a rather low uncompensated temperature coefficient of -135 ppm/ $^{\circ}\text{C}$ were measured for the 210 μm long and 1.5 μm thick beams. These resonators are considered to be attractive candidates for applications as resonant strain gauges in mechanical sensors, thus offering improved performance, with respect to resolution, selectivity and stability, as compared to their piezoresistive and capacitive counterparts.

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