CHAPTER 8

Examples and Applications

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PART II: SILICON DEVICES

8.II.1 Historical review[1]

The history of silicon resonant sensors is summarized in tables 8.1 and 8.2. These tables give an overview of the activities in the field from the beginning, in the late 1960's, until 1993. Table 8.1 reviews the prototype sensors. A project is included in this table if data on the response of the sensor has been published. Prototype resonant sensors are realized for measuring (differential) pressure, altitude, force, acceleration, mass flow, vapour and rotation. All sensors are based on stiffness modulation of the resonator except the vapour sensor [8.1.4], which is based on mass modulation. The remaining projects, resonators from which the response is not (yet) measured and resonators which have been used for other purposes like material characterization or characterization of excitation and detection mechanisms, are listed in table 8.2. Like all reviews, this review is not complete. Nevertheless, it gives a good insight in the activities and trends in the field.

The first devices date from the late 1960's and were made by Wilfinger et al. [8.2.1] and by Nathanson et al. [8.1.1]. That they were real pioneers is indicated by the fact that the next project is published more than 10 years after, in 1979. Since then, the number of projects has grown steadily.

Among the devices fabricated in the early 1980's, there were various resonant membrane (diaphragm) sensors [8.1.2], [8.1.5], [8.1.7]. These devices seemed to be ideal for pressure sensing (a pressure difference across the membrane stiffens it). However, they suffered from the problem that the frequency also shifted due to the mass of the gas in the vicinity of the membrane. Hence the resonance frequency was not only dependent on the pressure difference, but also on the sort of the gas and its temperature. This concept was soon abandoned, and a new generation in which the membrane itself does not vibrate, but instead of it, a resonator, e.g. a clamped-clamped beam, was fabricated on the diaphragm. The resonator stiffens as a result of the pressure induced statical deflection of the membrane. It is located in a reference pressure chamber, such that the mass of the vibrating gas is constant. A next generation arose

[1]From: A. Prak, *Silicon resonant sensors: operation and response*, Ch. 1 PhD Thesis, Univ. Twente, Enschede, the Netherlands

Table 8.1: A historical review on prototype resonant sensors in silicon technology

Ref	Name	Affiliation	Application	Year	Excitation Mechanism	Detection Mechanism	Major Resonator Material	Other Materials
8.1.1	Nathanson et al.	Westinghouse Res. Lab.	filter	1965	electostatic	electrostatic	gold	none
8.1.2	Smits et al.	Univ. Twente	pressure	1983	piezoelectric	piezoelectric	mono-Si	CVD glass ZnO 2 metal layers
8.1.3	Greenwood Andres et al.	STL, Harlow Univ. Valencia Univ. Surrey	pressure	1983	electrostatic piezoelectric optic	electrostatic optic	p++ mono-Si	none
8.1.4	Howe/Muller	Univ. Calif. Berkeley	vapour	1984	electrostatic	electrostatic	polySi	vapour sensitive polymer layer
8.1.5	Lammerink et al.	Univ. Twente	pressure	1985 1987	electrothermal optothermal	piezoresistive various optic	mono-Si mono-Si	p-diff,SiO2,Al -
8.1.6	Benecke et al.	Fraunhofer, Berlin	vibration	1985	base optothermal	piezoresistive interferometric reflection	epi p+Si	SiO2 poly gold (mass)
8.1.7	Bouwstra et al.	Univ. Twente	mass flow	1987 1990	electrothermal electrothermal	piezoresistive piezoresistive	p++mono-Si Si3N4	poly-Si poly-Si
8.1.8	Culshaw, Zhang Thornton, et al.	Univ.Strathclyde STC,	pressure	1988	optothermal	interferom		Al
8.1.9	Ikeda et al.	Yokogawa, Tokyo	pressure	1988	magnetic	magnetic	p++mono-Si	none
8.1.10	Blom, v Mullem et al.	Univ. Twente	force	1989	piezoelectr	piezoelectr	mono-Si	p++ ZnO metal
8.1.11	Chang, Putty, Howe	Univ. California Michigan, GM	acceleration	1989	electrostatic	electrostatic	poly-Si	none
8.1.12	Satchel and Greenwood	STC, Harlow	acceleration	1989	electrothermal	piezoresistive	mono-Si	p-implanted regions
8.1.13	Stemme Stemme	Chalmers Univ. Gotherburg	pressure altimeter	1990	electrostatic	optic	mono-Si	none
8.1.14	Petersen, Parsons et al.	Nova Sensor, Schlumberger	pressure	1991	electrostatic	piezoresistive	lightly n-doped monoSi	p implantation
8.1.15	Buser et al.	Univ. Neuchatel ABB	pressure	1991	base	interferom	mono-Si	none
8.1.16	Kvisterøy, Douma et al.	SensoNor, Shell Optoplan, Alcatel	pressure	1992	optothermal	optic	p++ mono-Si	chromium
8.1.17	Bernstein et al.	Charles Draper	gyroscope	1993	electrostatic	electrostatic	Nickel / p++ mono-Si on glass/ polysiliocn	
8.1.18	Bartelt et al.	Siemens	pressure	1992	optothermal	interferometric	Nitride	chromium
8.1.19	Seibert et al.	Schlumberger	pressure temperature	1993	optothermal	Fabry-Perot	Epitaxial Silicon	-
8.1.20	Cabuz et al.	Polytehnica, Bucharest/ Tohuku Univ.	Infrared	1993	electrostatic	electrostatic	p+	Si SiO2
8.1.21	Itoh, Suga	Univ. Tokyo	Dynamic AFM	1993	bulk piezoelectric	thin film piezoelectric	SiO2	ZnO/CrAu

Table 8.1. Cntd.

Shape of Resonator	Dimension [µm] Length x Width x Thickness	Mode of Vibration	Res Freq [kHz]	Qualit Factor (x1000)	Technology Keywords	Vacuum	Sensitivity	Temperature Sensitivity	Electronics
cantilever bridge		transversal	1 to 100	0.5 in air	SMM	no	-	90-150 ppm/C	integrated detection FET
membrane	1000x1000x5	transversal	200	0.15 in air	BMM TES	no	0.11 Hz/Pa		hybride freq. counter / feed back in I^2L
butterfly	1000 x 125 x 8	torsional and others	70	10	BMM BES	vacuum chamber			Ext. FET + AGC
perforated bridge	±150 x 50 x 1.35	transversal	250		SMM	no	0-10 deg phase over 0-1 part. press. xylene		integrated NMOS amplifier
diaphragm various	>1000x1000x15 2000x2000	transversal transversal	120 26	0.15	BMM TES	no	0.5Hz/Pa		all optic
cantilever with tip mass	600 to 1100 x 80 x 5	transversal	4 to 14 1 to 3	<0.1	BMM BES	no			
membrane bridge	2000x2000x2 600x200x2.1	transversal transversal	6 85		BMM BES	no no	175Hz/3mg/s 800Hz/10sccm	1200 Hz/C 600 Hz/C	bridge detect. bridge detect.
bridge	1600x70x2 700x20x2	transversal	72		BMM BES	no	156Hz/mbar		
H	1200x20x5	transversal	30	50	BMM BES	local vacuum	Gauge F= 3000	-40 ppm/C	external closed loop with AGC
bridge	6000x400x30	transversal	20	0.3	BMM TES	no	f/f0=5.2 at 0.25N		proposed: CMOS oscillator
bridge	250x100x1.6	transversal	65	?	SMM	vacuum chamber	160 Hz/g		NMOS electronics
			65	2.7 in air	BMM	no	1.4Hz/m/s2	-22ppm/C	
membrane	14000x14000 x720	torsional	17	3 air 80vac	BMM SFB		14 to 19%/bar	1.3 ppm/C	
bridge	600x40x6	transversal	110	60 to 180	BMM SFB	vacuuum chamber	8%FS/bar	20 ppm/C	
bridge and others		transversal	25-60	2 - 5 60	BMM SFB	vacuum chamber	2%/bar 4E-9/pa	26 ppm/C	
butterfly		torsional	84	20 to 40	BMM BES	vacuum chamber	52 Hz/bar	14 Hz/C	
comb	700x700x5	lateral		up to 1	SMM		5000 °/hour		
bridge	577x6x	transversal	130	0.03	BMM		30 kHz/Bar	40 Hz/C	
bridge cantilever	600x40x5 180x40x5	transversal	120 200	10		vacuum chamber	0.12 kHz/kPa -8 Hz/C		all-optic
bridge	2000x200x2	transversal	50	2	BMM		500 ppm/µW		NMOS on chip
cantilever	250x50x2	transversal	150	0.3	BMM				

*) BMM=bulk micro-machining; SMM=surface micro-machining; BES=boron etchstop; TES=time etchstop; SFB=silicon fusion bonding

Table 8.2: A historical review on resonant silicon test structures and proposed prototype sensors

Ref	Name	Affiliation	Subject of Research	Year	Excitation Mechanism	Detection Mechanism	Major Resonator Material	Other Materials
8.2.1	Wilfinger et al.	IBM	characterizing the device	1966	electrothermal	piezoresistive	mono-Si	
8.2.2	Petersen et al.	IBM	determination of Y-modulus	1979	electrostatic	optic	SiO2, Si3N4	metal
8.2.3	Culshaw, Zhang Uttam Thornton et al.	Univ. Strathclyde	optical exc temperature dependence	1985	optothermal	optic	p+ mono-Si or SiO2	aluminium
8.2.4	Guckel, Sniegowski et al.	Univ. Wisconsin Honeywell	pressure accelerom	1987	electrostatic	piezoresistive	poly-Si	boron
8.2.5	Hane et al.	Nagoya Univ.	optothermal excitation	1988	optothermal	interferometric	glass or Si	several coatings
8.2.6	Bouwstra et al.	Univ. Twente	demonstrate exc/det mechanism	1989	electrostatic using thin film	electrostatic using thin film	mono-Si	p++ Si3N4 Au
8.2.7	Tang, Lin, Nguyen Howe et al.	Univ. California	filter oven control	1989 1993	electrostatic	electrostatic visual	poly-Si	
8.2.8	Buser et al.	Univ. Neuchatel	high Q temp dep press dep	1989	base magnetic	interferometric	mono-Si	none metal
8.2.9	Linder et al.	Univ. Neuchatel		1990	electrostatic	electrostatic	poly-Si P-doped	
8.2.10	Stokes, Fatah	Univ. Coll. London	characterizing the device thermal excitat	1990 1992	electrost/ optic optic	optic	SiO2 or Si3N4 Si/SiO2/Si3N4	gold or aluminium
8.2.11	Roszhart	Kearfott GNC Little Falls	intrinsic Q	1990	electrostatic	electrostatic	mono-Si	none
8.2.12	Lammerink Prak	Univ. Twente	thermal excitat electronic strain	1990	electrothermal optothermal optic	interferometric	Si	metal
8.2.13	Tabib-Azar et al.	Univ. Cleveland	direct optical excitation	1990	opt. modulation of biased air gap capacitor		p++ mono-Si	none
8.2.14	Blom, Prak et al.	Univ. Twente	Q-modeling	1990 1991	optothermal	interferom	mono-Si mono-Si	p++
8.2.15	Conally, Brown	C.S.Draper Lab, MIT,Cambridge	fatigue testing crack growth	1991	electrostatic	electrostatic	p++ mono-Si	gold end mass
8.2.16	Suski et al.	Schlumberger Univ. Twente	ZnO optical excitation	1990	ZnO optic	optic	mono-Si	SiO2, ZnO
8.2.17	Moser et al.	ETH Zurich	acoustic radiation	1991	electrothermal	optic	SiO2	Al, poly-Si
8.2.18	Prak et al.	Univ. Twente	selective mode excitat/detection dynamic respons	1992 1993	electrostatic air gap/thin film	interferom electrostatic	mono-Si	Al p++,Si3N4,Au
8.2.19	Tabib-Azar et al.	Univ. Cleveland	aging	1992	electrostatic	electrostatic	p++ mono-Si	none
8.2.20	Baizar et al.	Polytech Inst Lvov, Univ sofia	electronic circuitry	1992	electrostatic	electrostatic		
8.2.21	Bouwstra et al.	Univ. Twente Univ. Michigan	base excitation	1992	electrothermal	interferometric	p++ mono-Si	
8.2.22	Tilmans et al.	Univ. Twente Johnsons	pressure	1992	electrostatic	electrostatic	poly-Si	
8.2.23	Kiesewetter et al.	TUBerlin Siemens	determination of Y-modulus	1992	various	optic	Si3N4	
8.2.24	Mihailovich et. al.	Cornell Univ.	clamping losses	1993	electrostatic	electrostatic	mono-Si	
8.2.25	Nikolich, Senturia, Shirley	MIT	electronic feed back loop	1992	magnetic	magnetic	mono-Si	

Table 8.2: Cntd.

Shape of Resonator	Dimension [μm] length x width x thickness	Mode of Vibration	Res Freq [kHz]	Quality factor (x1000)	Technology Keywords *)	Vacuum	Temperature Sensitivity	Electronics
cantilever	5000x500x 125	transversal	0.6 to 200	0.25 to 4.4	BMM	no	36/74ppm /C	integr. transistor detection bridge
cantilever	typical 50x5x0.1	transversal	20-100	0.003- 0.001	Epitaxial layer	no		
bridge diaphragm	typical 1000x12x2 760x760x4	transversal	80	3 invac 0.1 air	BMM	no	60 Hz/C	
bridge	200(600)x45x2	transversal	330 to750	0.01 to 35	SMM	sealed	-75 ppm/C	external closed loop with AGC
circular plate	e.g. 12000x80	transversal	1	0.06	-	no		
cantilever	typical 5000x300x30	transversal	2	0.3	BMM TES	no		
comb		lateral	20	0.1 air 50 vac	SMM			on chip detection
bossed beam various		transversal	2.5	600	BMM TES	external	40 ppm/C	
bridge	typical 300x25x1	transversal	120	very low	SMM			NMOS detection Amplifier
bridge	200x20x1	transversal	15 to 60 200 - 400	0.01 0.4	BMM	no	4400 ppm/C	
cantilever bridge	typical 200x30x10	transversal	86 to 650	9 to 70	BMM	bell-jar		
cantilever/ bridge	various	transversal	1-50	typical 0.1	BMM TES	in air	bridge: >>75ppm/C	
cantilever	typical 600 x 50 x 2	transversal			BMM BES	in air		
cantilever membrane	various	various		0.1 to 5	BMM TES	bell-jar		
cantilever	130x11.5x2.9	transversal	2.5	<0.1	BMM BES	no		
cantilever	10000x1500x50	transversal	0.35	0.1	BMM TES	no		
cantilever	300x100x?	transversal	10	0.04	CMOS+ BMM	no		
bridge	5000x1000x 20	transversal	10	0.1 to 1	BMM TES	bell-jar		
cantilever	600x50x1.78	transversal	6	0.5	BMM BES	no		
fiber								external electronics
cantilever	typical 500 x 200 x 3	transversal	6	0.06	BMM BES	no		
bridge	typical 500 x 100 x 1	transversal			SMM	local vacuum		bridge capacitor
cantilever	typical 1000x100x0.54	transversal	1-12	0.02				
grid	Typical 100x50x3	torsional	160		SCREAM			
H	2400x20x5	transversal	46	40	Bond and etch back			external feed back

*) BMM=bulk micro-machining; SMM=surface micro-machining; BES=boron etchstop; TES=time etchstop; SFB=silicon fusion bonding; SCREAM=single crystal reactive etch and metal

at the end of the 1980's, when the reactive sealing technique originated: resonators were sealed in local vacuums, fabricated using micromachining techniques, to ensure high quality factors [8.1.9], [8.2.4] and [8.2.22]. This concept will probably be used in most future resonant pressure sensors.

Around 1990, the lateral resonators came in vogue [8.2.7], [8.1.17], [8.2.24]. These resonators, vibrating parallel to the substrate, are fabricated by the surface micromachining technique, which will probably dominate in the future.

Most resonators are made of silicon, either in mono or polycrystalline form, with high or low doping levels. However also non-silicon resonators were fabricated. The early resonators of Nathanson [8.1.1] are an example: they were made of gold. Later on, resonators of silicon-nitride (Si_3N_4) and silicon-oxide (SiO_2) were reported. All non-silicon resonators were fabricated with silicon technology and fit as such in the category 'silicon resonant sensors'.

A variety of 'strange' materials used as thin films is reported. Most of them are used in connection with the transducers for excitation and detection. Metal coatings of e.g. aluminium, chromium and gold are commonly used for electrical conduction, but also for photon absorption. Heavily boron doped silicon can also be used for electrical conduction. Besides, this material can serve as an etchstop. Poly-silicon is widely applied for its good piezoresistive properties, and zincoxide (ZnO) for its piezoelectric properties. Further, isolation layers of silicon-nitride and silicon-oxide are used.

Nowadays, two silicon resonant sensors are commercially available. The first is a sensor for atmospheric pressure made by Druck Ltd [2], see fig. 8.1.a. This sensor is based on the concept of Greenwood [8.1.3]: an electrostatically operated 'butterfly'-shaped resonator, realized by a boron etchstop is placed on a silicon diaphragm, which deflects under influence of atmospheric pressure. The resonator is placed in an vacuum tube. The accuracy is 0.1 %. Temperature effects are software compensated, using a calibration curve.

The second one, is a differential pressure sensor made by Yokogawa Electric Corporation [3] [8.1.9], see fig. 8.1.b. This sensor is also realized using a boron etchstop. The Yokogawa sensor has magnetic excitation/detection. It is realized using a local sealing technique: the vacuum is created in one of the silicon processing steps. The sensor is available for various differential pressure ranges from 10 kPa to 14 MPa. The accuracy is also 0.1 % and temperature effects are also software compensated.

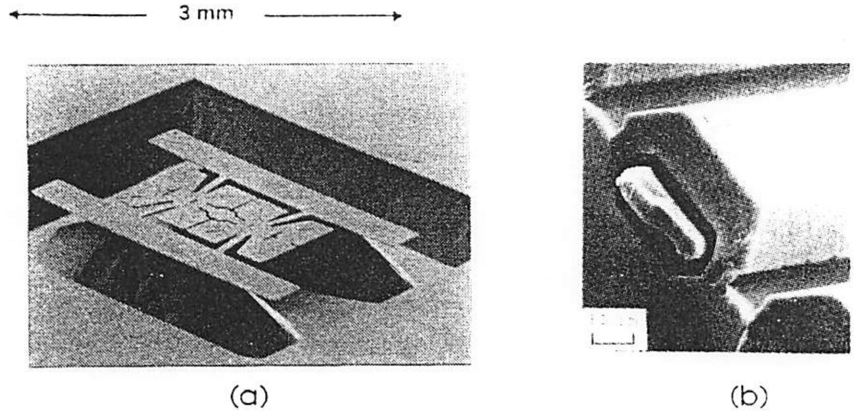
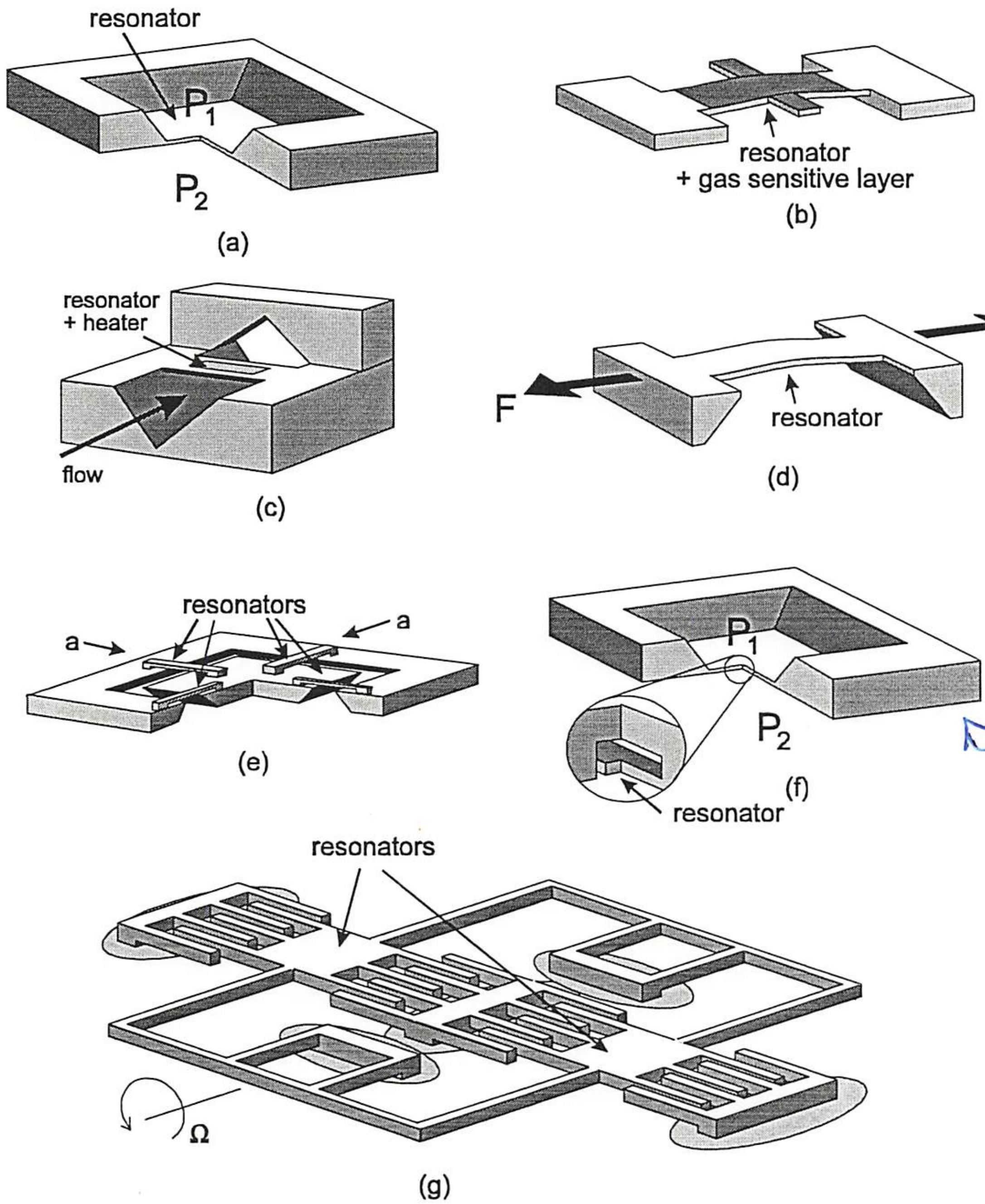


Fig. 8.1. The heart of the two today commercially available micromachined resonant sensors. (a) the Druck pressure sensor and (b) the Yokogawa pressure sensor.

2) Druck Limited, Fir Tree Lane, Groby, Leicester LE6 OFH, England

3) Yokogawa Electric Corporation, 9-32, Nakacho 2-chome, Musashino-shi, Tokyo 180, Japan



BOD

Fig. 1.3: Examples of silicon resonant sensors. (a) resonant diaphragm pressure sensor [8.1.2]; (b) resonant microbridge vapour sensor [8.1.4]; (c) resonant microbridge mass flow sensor [8.1.7]; (d) resonant beam force sensor [8.1.10]; (e) two axes accelerometer [8.1.11]; (f) resonant beam on diaphragm pressure sensor [8.1.14]; (g) lateral resonating comb drive gyroscope [8.1.17]; note that the gyroscope is not a resonant sensor in the sense that the frequency depends on the measurand. In some cases, the devices are depicted somewhat simplified. Excitation and detection transducers are not shown. BOD

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8.II.2 The Yokogawa sensor [8.1.9]

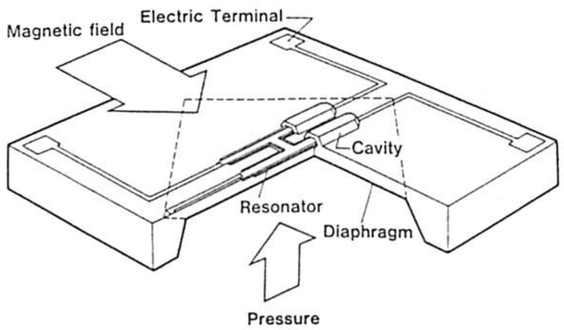


Fig. 1. Construction of silicon resonant pressure sensor.

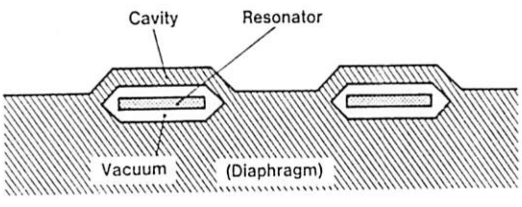


Fig. 2. Cross-sectional view of the strain gauge.

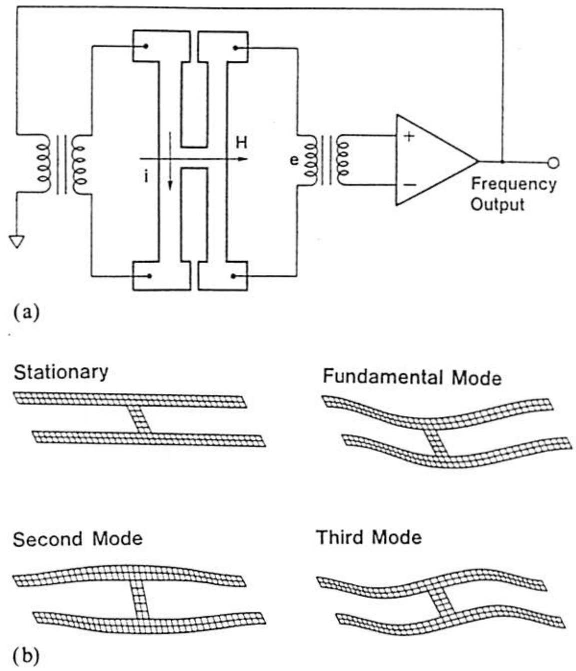


Fig. 3. (a) Schematic diagram of resonant strain gauge. (b) Several resonant modes of the resonator.

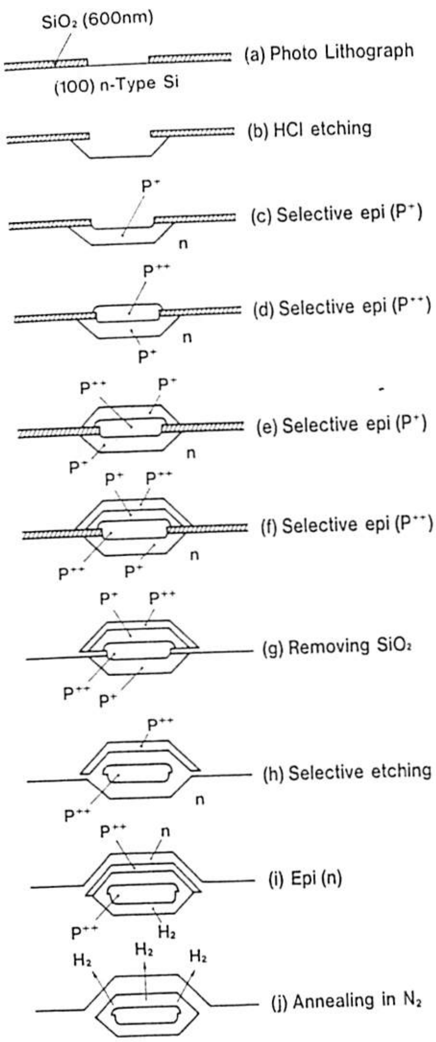


Fig. 4. (a)–(j) Fabrication process of resonant strain gauge.

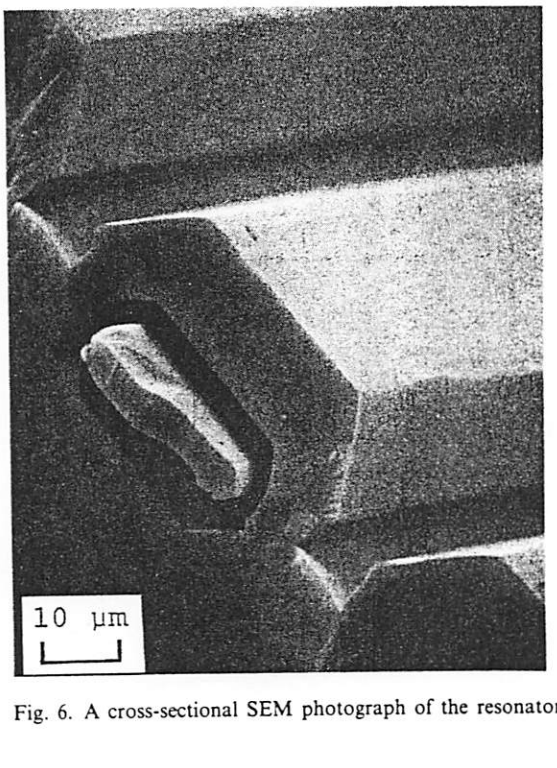
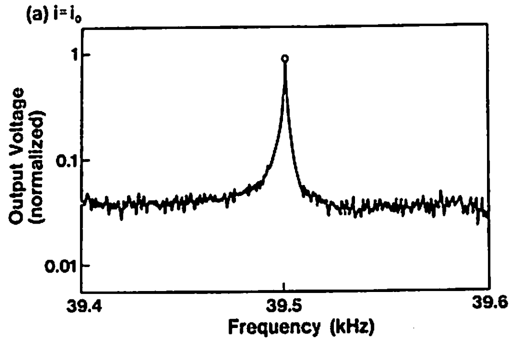
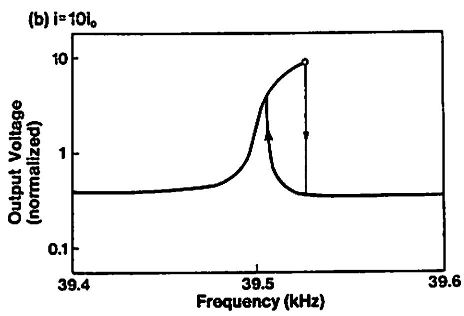


Fig. 6. A cross-sectional SEM photograph of the resonator.



(a)



(b)

Fig. 8. Frequency response of the resonator: (a) small amplitude; (b) large amplitude.

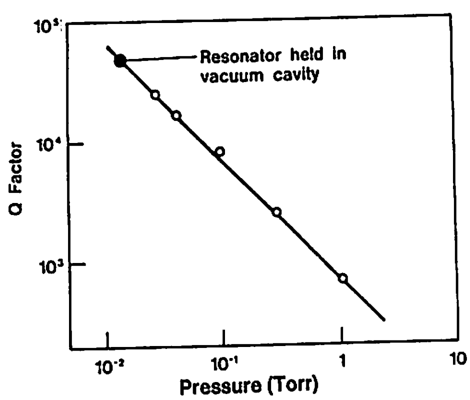


Fig. 7. Relationship of pressure to Q factor.

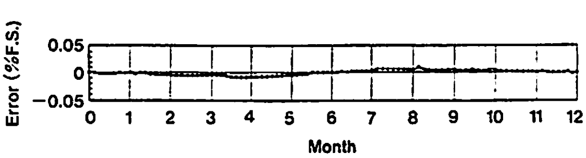
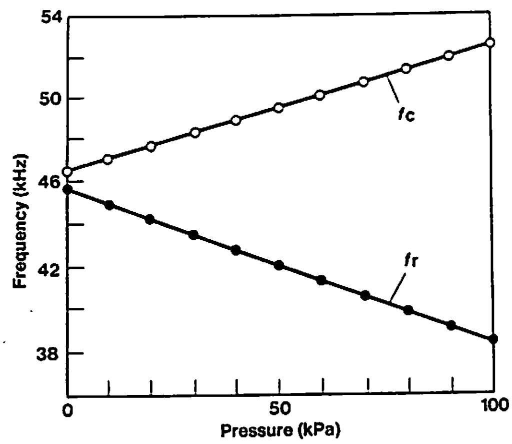
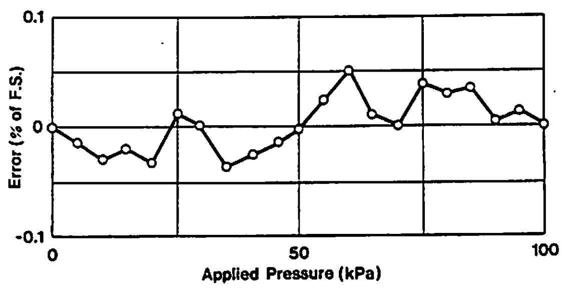


Fig. 9. Long-term stability of resonator.



(a)



(b)

Fig. 7. Relationship of input pressure to output frequencies (a); curve fitness to the third-order equation (b).

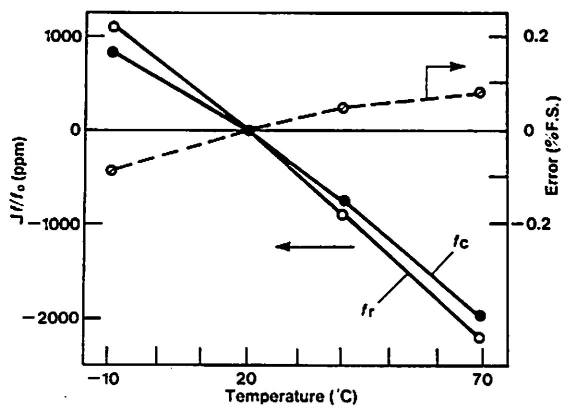


Fig. 11. Temperature characteristics of the resonant strain gauge, ○ and ● are inherent characteristics, and ⊘ is a differential characteristic.

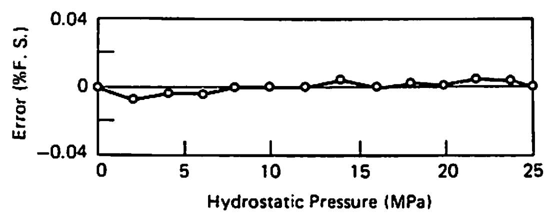
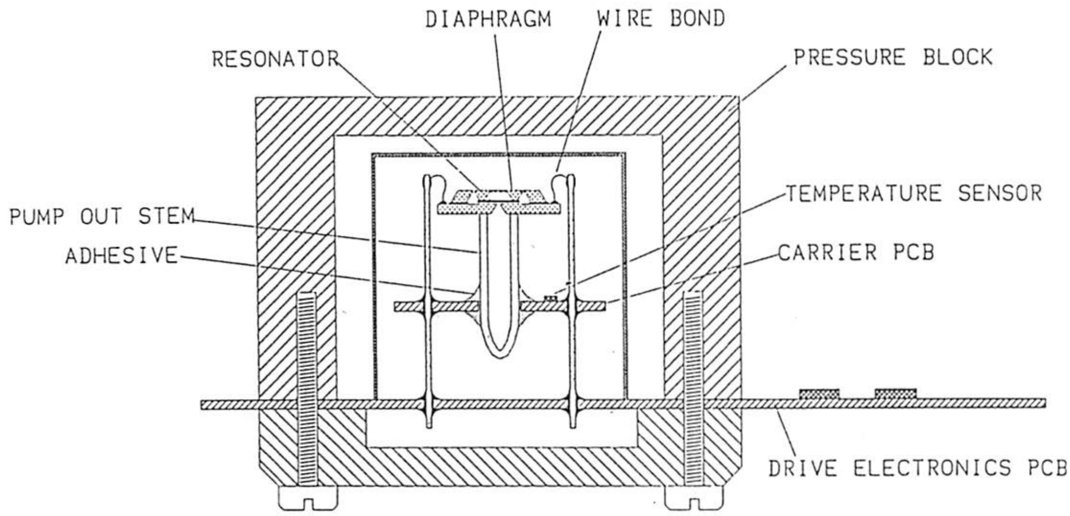


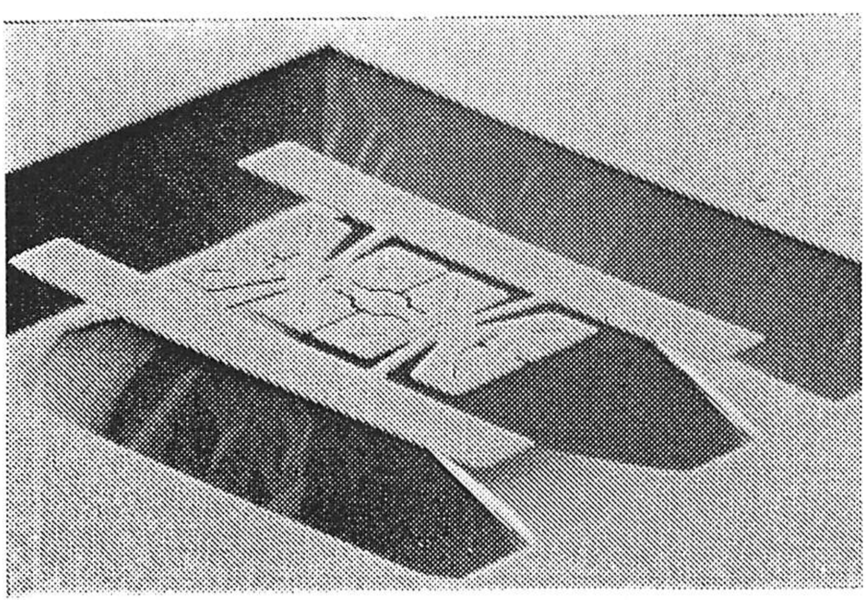
Fig. 12. Hydrostatic pressure effect.

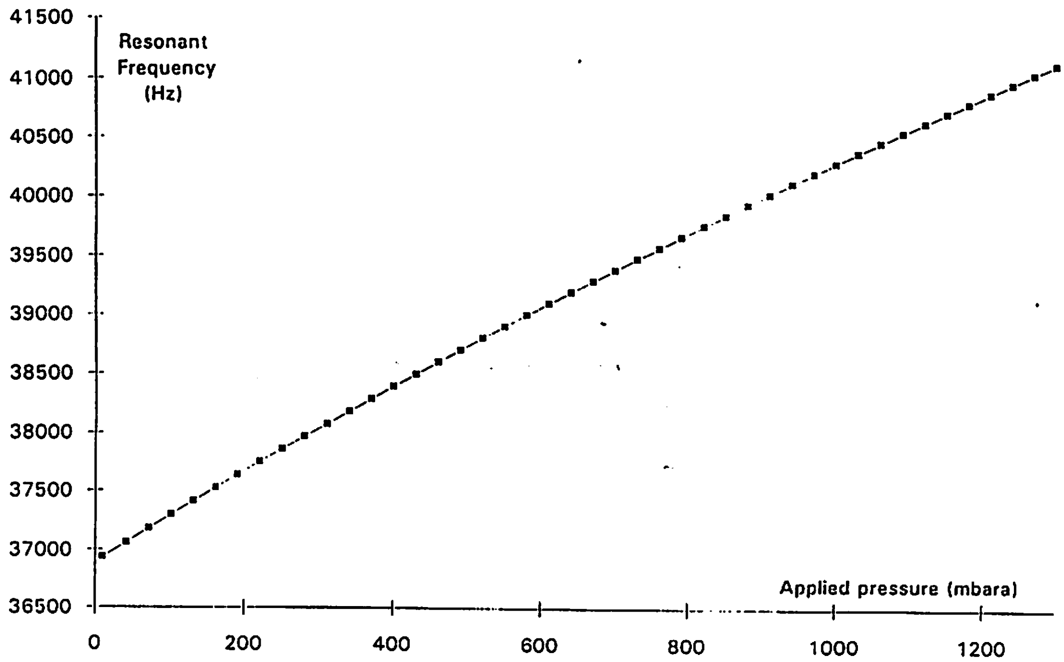
8.II.3 The Druck sensor (Greenwood) [8.1.3]

Research on this atmospheric-pressure sensor started in the early 1980's. A commercial device resulted in the early 1990's. The device is realized using a boron etch-stop mechanism. Vacuum is obtained by conventional techniques, rather than micromechanical sealing techniques. The commercial device has electrostatic excitation/detection. However, for research purposes, optical operation has also been applied. The sensor has some spin-offs [8.1.16], which are characterized by the typical butterfly-shaped resonator.

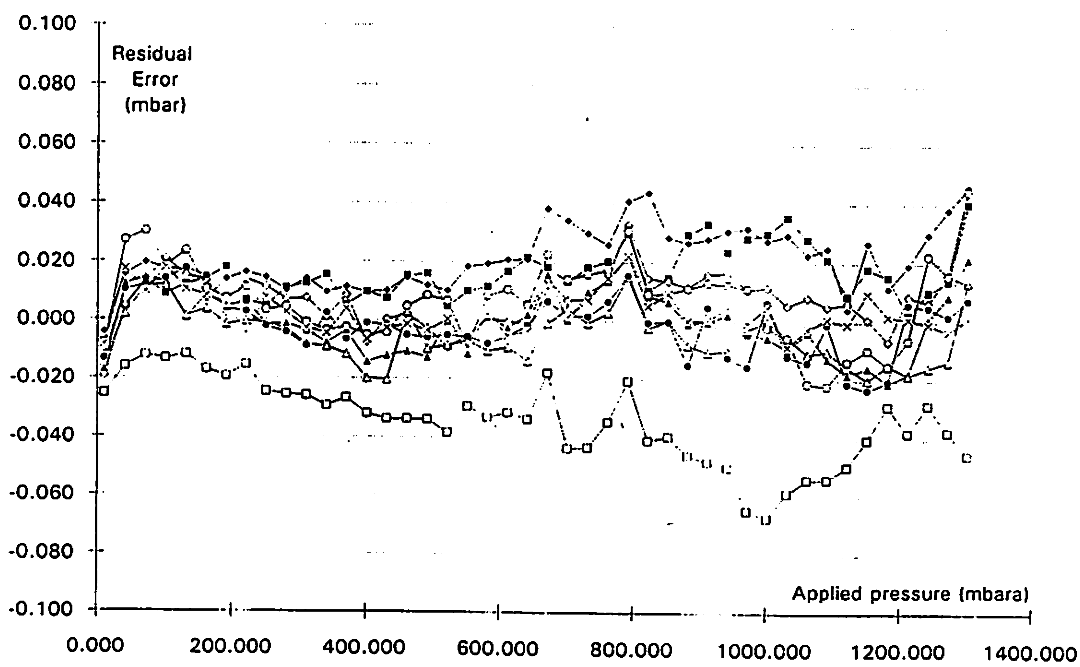


Diagrammatic cross section of the complete sensor





Resonant frequency vs applied pressure.



Residual error -25°C to 75°C.

8.II.4 The Berkeley Devices [8.1.4, 8.1.11, 8.2.7]

The process developped at the University of California at Berkeley is a typical surface micromachining technology, which is very flexible. Numerous resonant devices have been realized using this process. The process is a so called sacrificial layer process, which means that a 'temporary layer' is deposited, on top of which other layers are depositred out of which the resonators are created. The temporary layer is sacrificed in a later stadium in order to release the resonators. In the Berkeley process, the sacrificial layer is made of Poly Silicate Glass (PSG), while the resonators are made of polysilicon. The process can be repeated several times. In this way multiple layers on top of one another (with poly in between) can be removed in order to create hollow resonators or vacuum encapsulated resonators. Most resonators fabricated in this way are vibrating parallel to the substrate (lateral resonators) They are electrostaically excited and detected using a comb-structure.

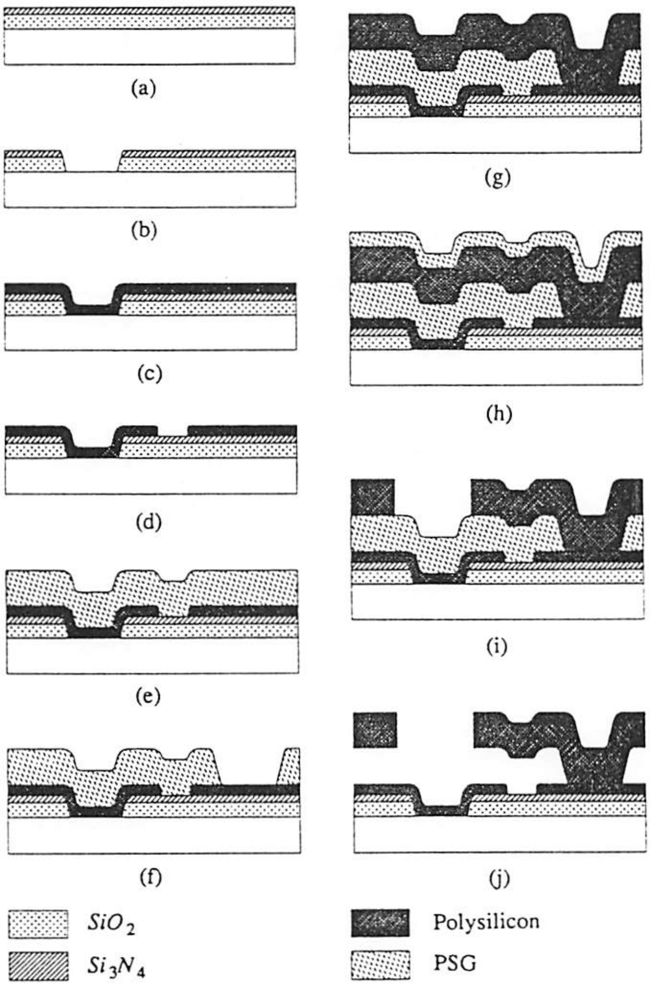


Fig. 4. Process sequence of a lateral resonant structure. (a) Deposition of LPCVD nitride on top of a layer of thermal SiO_2. (b) Contact windows to substrate n+ diffusion. (c) Deposition of *in situ* P-doped LPCVD polysilicon. (d) Patterning of first polysilicon layer. (e) Depositon of sacrificial PSG. (f) Anchor windows for second polysilicon layer. (g) Deposition of the undoped LPCVD polysilicon structural layer. (h) Deposition of second layer of PSG for doping symmetry. (i) Patterning of second polysilicon layer. (j) Final cross section after wet etching of sacrificial PSG.

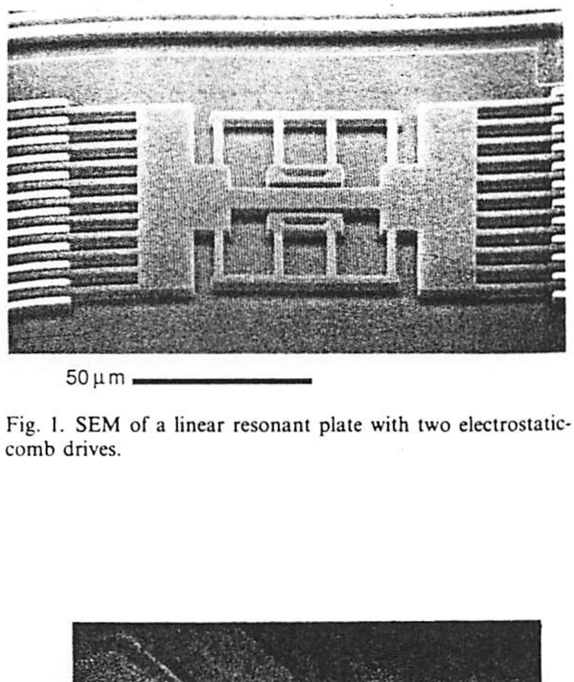


Fig. 1. SEM of a linear resonant plate with two electrostatic-comb drives.

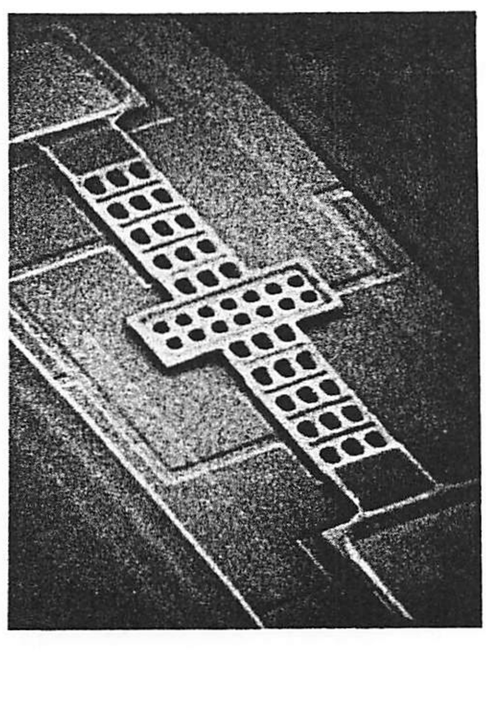


Figure 4. SEM of apertured type C microbridge.

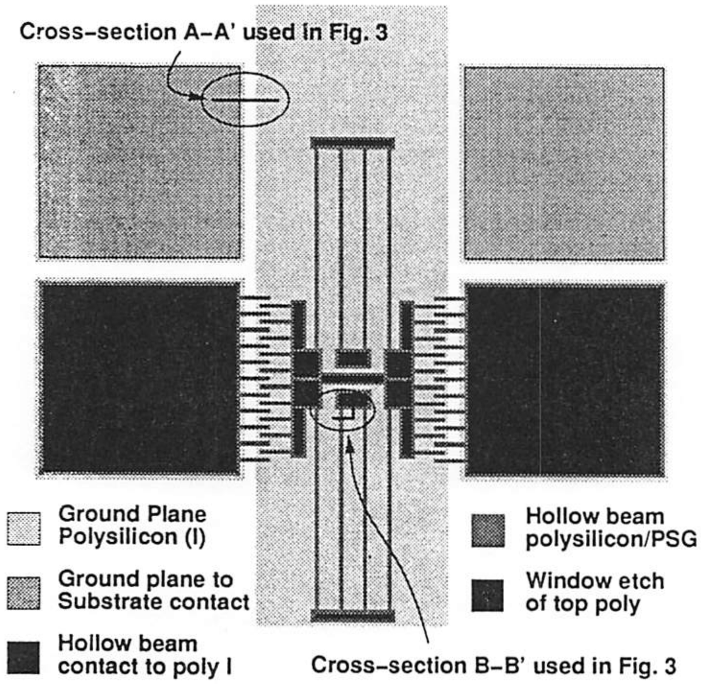


Figure 2: Layout of hollow beam lateral resonator. The cross sections in Figure 3 are taken between A—A' and B—B'.

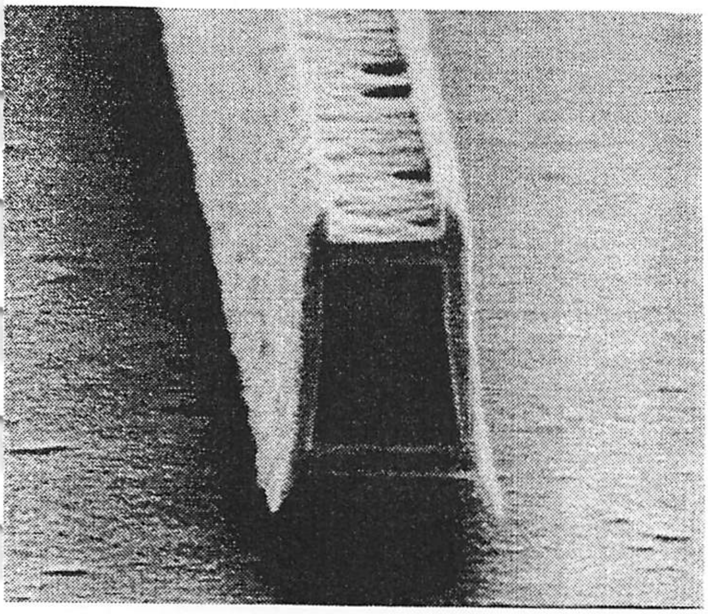
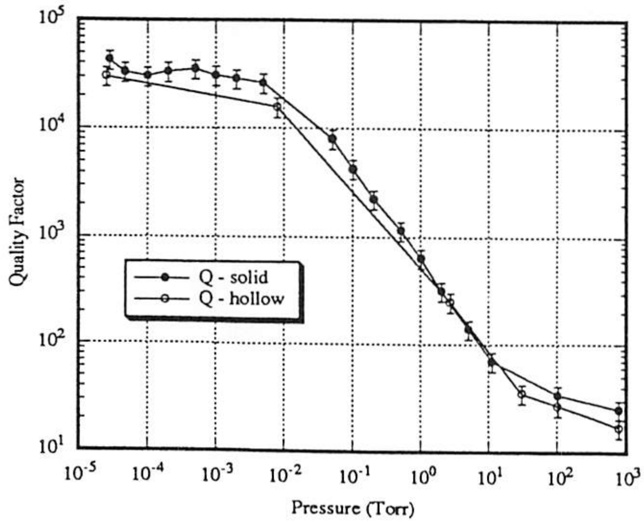


Figure 6: SEM cross section of a hollow beam 2 μm-wide and 2.5 μm-tall. The polysilicon walls are 0.3 μm-thick.



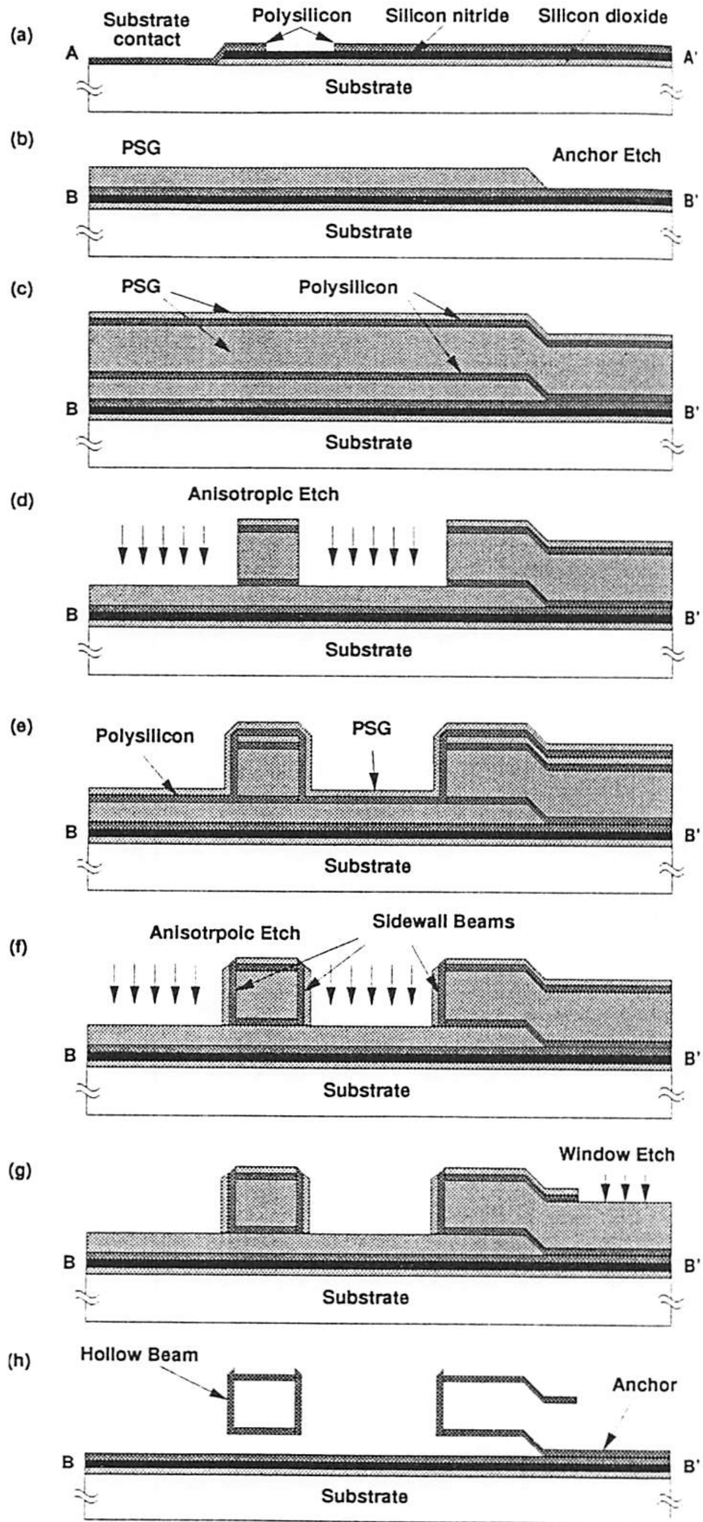


Figure 3: Process sequence cross sections for polysilicon hollow beams: (a) silicon dioxide and silicon nitride passivation, subtract contact etch, polysilicon ground plane deposition and etching; (b) 2.0 μm phosphosilicate glass (PSG) deposition and contact and dimple etches; (c) depositions of polysilicon (bottom of hollow beam), PSG (inside hollow beams), polysilicon (top of hollow beam) and PSG; (d) anisotropic etch of oxide/poly/oxide/poly sandwich; (e) deposition of polysilicon (sidewall of hollow beam) and PSG; (f) maskless anisotropic etch of PSG and polysilicon forming sidewall spacers; (g) etching of top PSG and polysilicon; (h) release etch and dry.

8.II.5 The Wisconsin sensor [8.2.4]

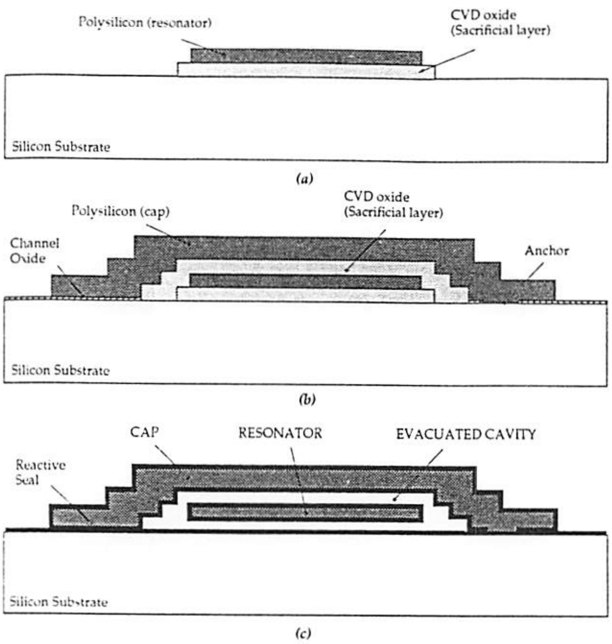


Fig. 2.8. Fabrication process of sealed resonant force gauges using LPCVD polysilicon [2.43]. (a) after deposition and patterning of the first sacrificial layer (CVD or thermal oxide) and the first polysilicon layer. (b) after deposition and patterning of the second sacrificial layer (CVD oxide or nitride), thin thermal oxide for the etch channels and the second polysilicon layer. (c) after the sacrificial layer etch in HF and reactive sealing with polysilicon or silicon nitride.

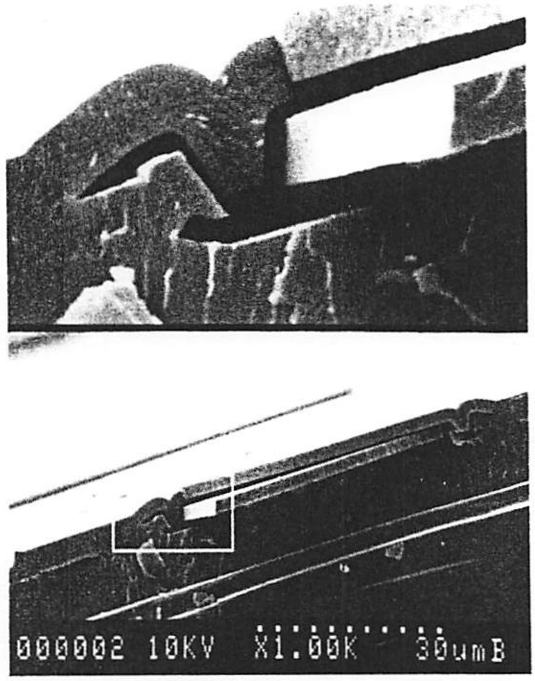


Fig. 4. SEM cross-sectional photograph of the completed structure. The beam is 45 μm wide and 2.3 μm thick. A 5× magnification from a portion of the cavity is shown in the upper photograph. The gap from beam to substrate is 1.1 μm and the gap from beam to top cover polysilicon is 1 μm.

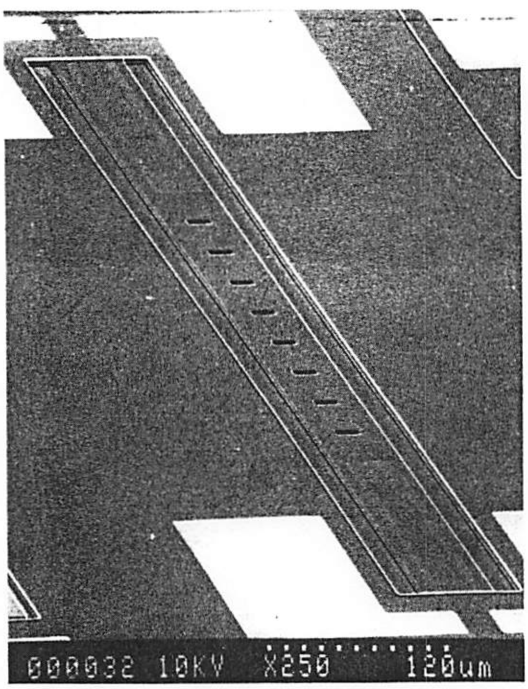


Fig. 5. SEM photograph of open beam structure showing the implanted resistor configuration. Beam dimensions are 60 × 600 μm.

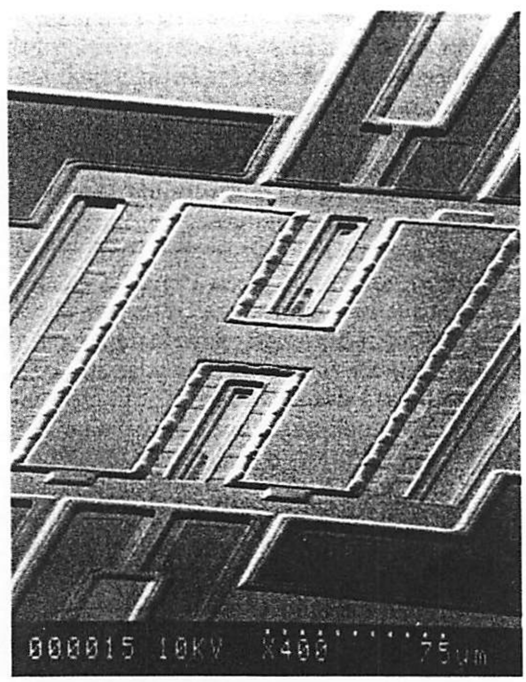


Fig. 7. SEM photograph showing the top view of an H-resonator. Dimensions of the two main beams are 45 × 300 μm while the cross member is 41 μm wide and 55 μm long. The ribbed outline around the H-beam indicates where the etch channels were defined.

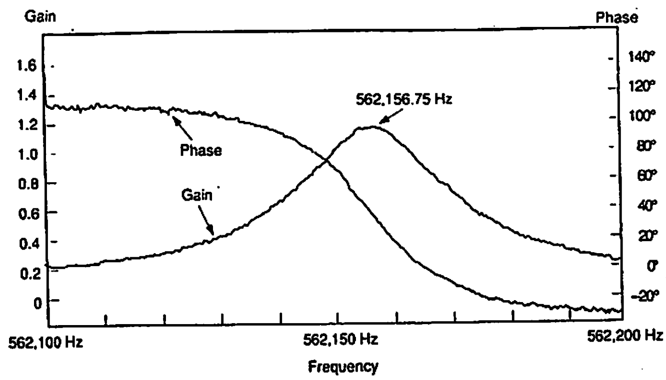
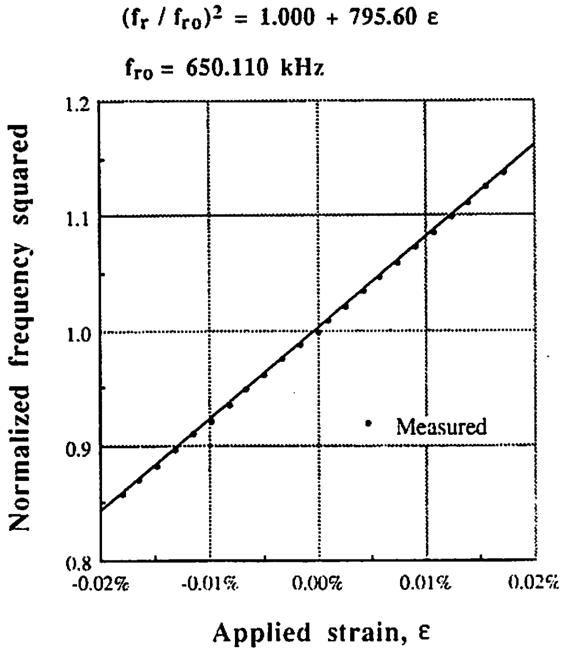


Figure 2b. Bonded device gain-phase measurements. Improved signals are obtained after packaging and bonding the device shown in Figure 2a.



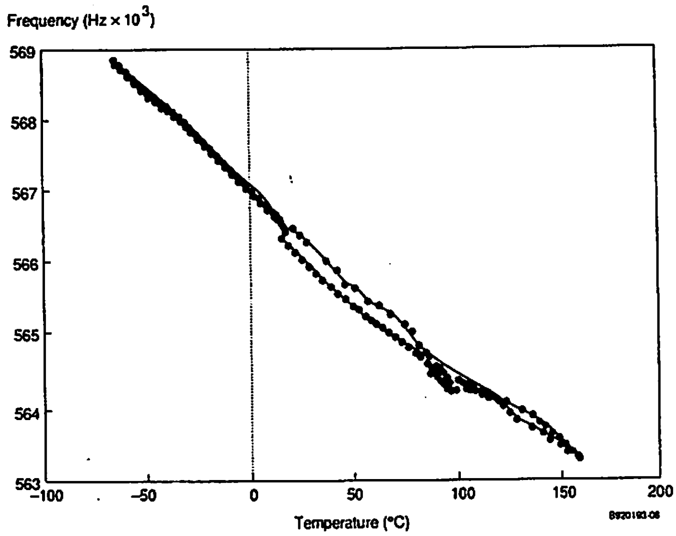


Figure 3. Frequency variation with temperature. Temperature excursions from -60°C to over 160°C result in less than a 1% total shift in resonant frequency of a resonant microbeam.

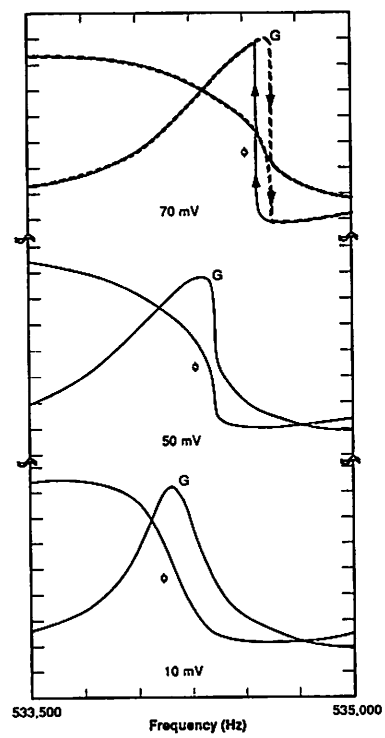


Fig. 4. Nonlinear behavior of microbeam resonators. As the drive amplitude is increased, the resonance shifts to higher frequencies, and the frequency response becomes asymmetric, eventually showing amplitude discontinuities and hysteresis as the frequency is swept. ----, Increasing frequency: · - ·, decreasing frequency. Drive voltage = 10, 50, 70 mV rms; G = gain (0.5/div.); ϕ = phase (20 /div.).

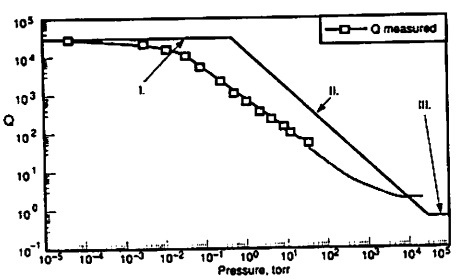
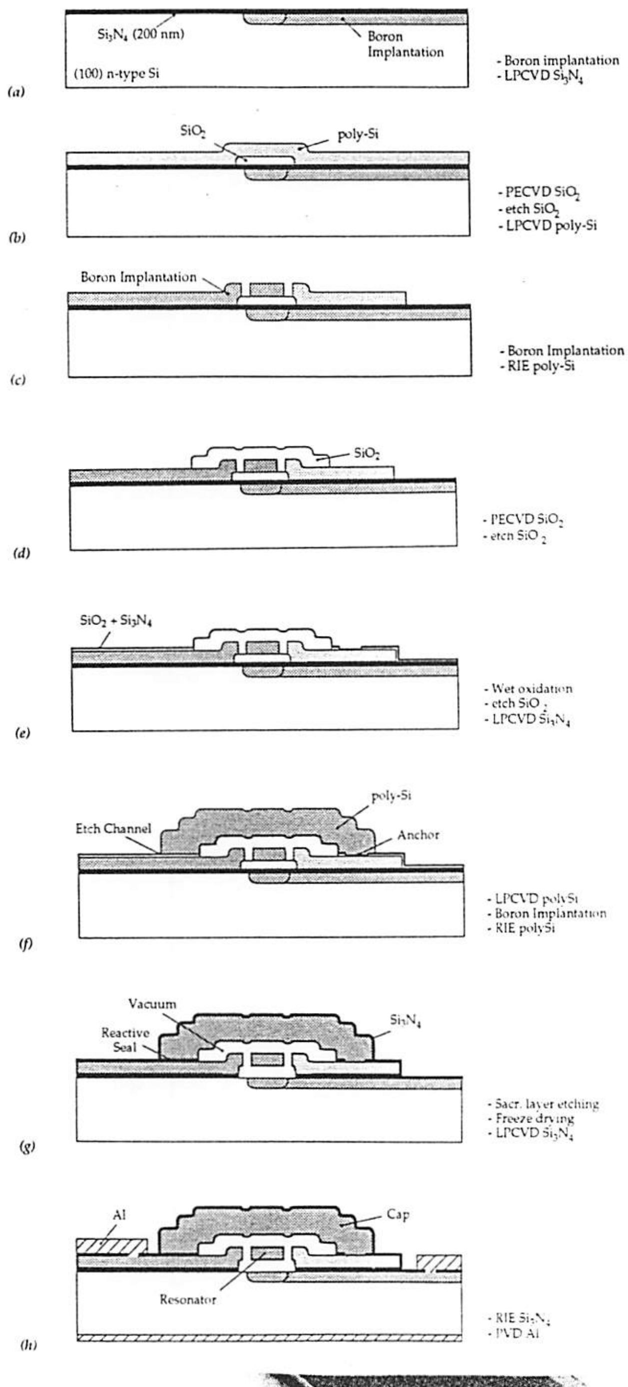


Fig. 5. Quality factor vs. external pressure for a 200 μm long, 40 μm wide microbeam. The theoretical predictions of Q are designated by the solid lines in the three regions. Region I corresponds to the observed limit Q of the resonator. II is the region of momentum damping by collisions with individual gas molecules, while III is the region of viscous damping.

8.II.6 The Twente sensor [8.2.22]



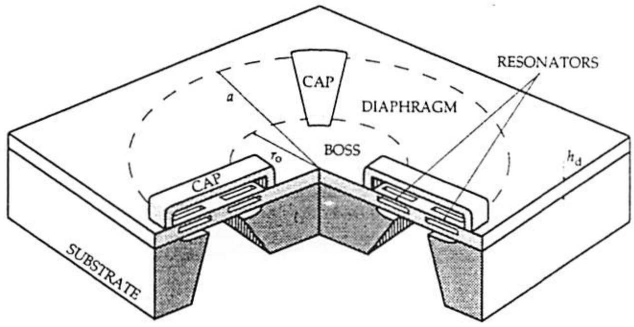


Fig 6.3. 3-D sketch of a differential pressure sensor based on a differential resonator design employing a circular bossed diaphragm.