

Fundamentals and State of the Art

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(Received June 13, 1995; accepted June 10, 1996)

Key words: resonant sensors, silicon, quartz, gallium arsenide, Q-factor

Resonant sensors offer a high-performance solution to many sensing applications. We present a review of resonant microsensors based upon resonant structures fabricated in silicon, quartz and gallium arsenide. The methods of coupling the resonator to the measurand are discussed and example sensors for pressure, acceleration and rotation sensing applications are introduced. Important design considerations such as resonator geometry, the Q-factor, nonlinear behaviour, power consumption and packaging are analysed. Lastly the relative merits of silicon, quartz and GaAs as a resonator material are reviewed.

1. Introduction

Resonant sensors offer high accuracy (0.01%FS), low drift (ppmFS/year) and high resolution. However conventional resonant sensors have required painstaking machining of the metal resonator and careful hand assembly of the complete sensor. Their excellent performance characteristics have justified their use in applications such as aircraft engine management systems and high-accuracy pressure controllers, but the high cost of conventional resonant sensors has prevented their widespread application.

Micromachined resonant sensors or resonant microsensors are fabricated in batches on silicon, quartz or gallium arsenide wafers. They are therefore significantly cheaper and smaller than conventional resonant sensors with a performance which should be comparable to, if not better than, that of conventional devices. It is therefore probable that resonant microsensors will be more widely applied than their conventional predecessors.

We review the fundamental operating principles of resonant microsensors and the current state of the art. This paper is complementary to other recent review articles.^(1,2) Examples are given of the most important types of resonant microsensors: pressure sensors, accelerometers and gyroscopes. Then, the design rules for resonant sensors are outlined followed by a discussion of the materials and fabrication techniques which can be used in the manufacture of microresonant devices. Finally the most important resonator cross sensitivities are outlined.

2. Basic Principles of Resonant Sensors

Figure 1 shows a block diagram of a typical resonant sensor. The heart of the resonant sensor is a mechanical structure vibrating at its resonant frequency. The vibrations are excited by some form of drive technique (*e.g.* electrostatic) and sensed by some form of detection technique (*e.g.* piezoresistive). Drive and detection can be separate (two-port configuration) or combined (one-port configuration).⁽³⁾ Electronic circuitry, usually either a simple amplifier or a phase-locked loop, provides feedback from detection to drive. By this means the resonator is maintained in continuous vibration at its resonant frequency.

The predominant form of resonant microsensor provides a frequency output; that is its mechanical structure's resonant frequency is a function of the measurand. This has been achieved in three ways: by applying a force or stress to the resonator thus changing its stiffness, by altering the mass of the resonator or by changing the shape of the resonator.^(1,2) The stiffness effect has been applied in micromachined pressure sensors⁽⁴⁻⁶⁾ and accelerometers.⁽⁷⁻⁹⁾ The added mass effect has been used in the quartz crystal microbalance which is often used as a thickness monitor in thin film coating systems⁽¹⁰⁾ and the shape effect has been applied to realise a pressure sensor.⁽¹¹⁾

The stiffness and added mass effects are the most commonly applied to date and are illustrated in Figs. 2 and 3. Figure 2 shows the change in frequency of modes 1 to 3 of a

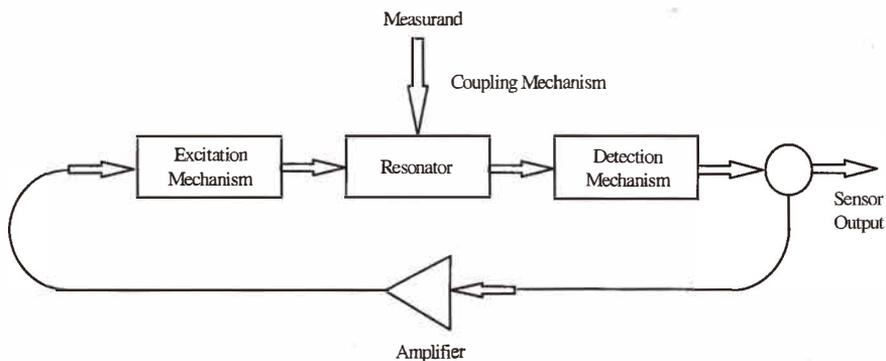


Fig. 1. Block diagram of a resonant sensor.

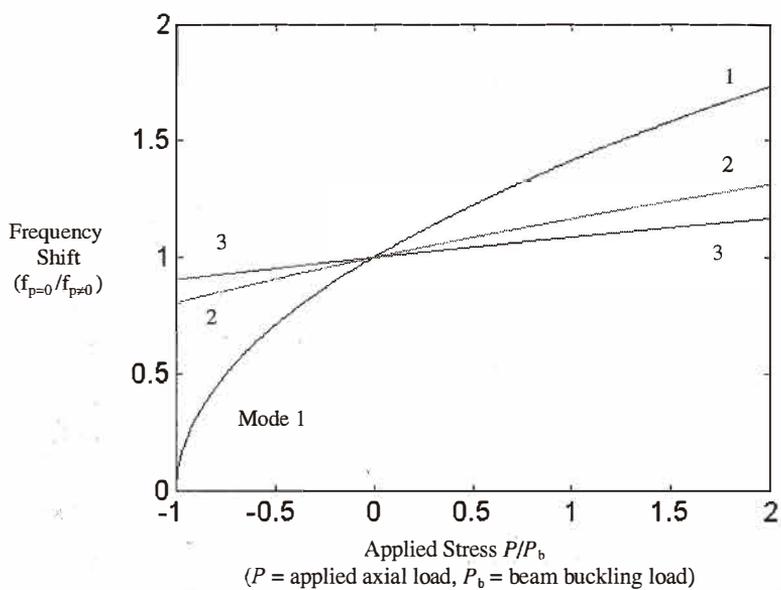


Fig. 2. Stiffness-induced frequency change.

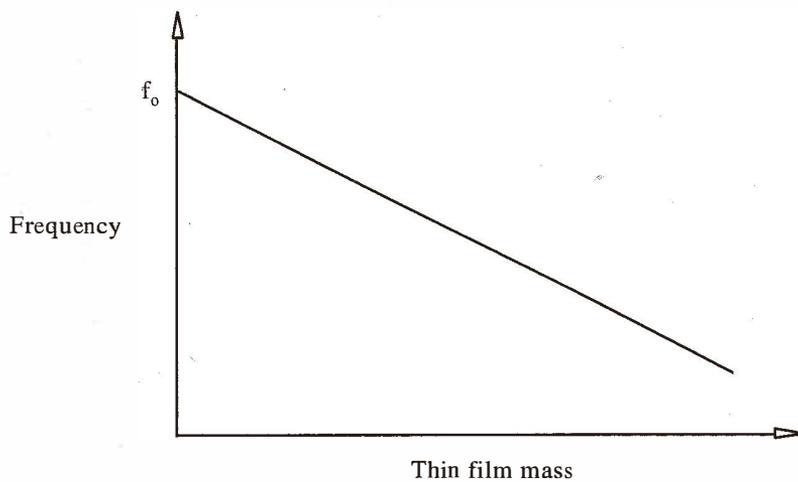


Fig. 3. Added-mass-induced frequency change.

clamped-clamped beam in response to applied axial loads. The frequency shift plotted is relative to the unstressed frequency for each mode. The figure shows the effects of both compressive and tensile loads, the applied load being plotted with respect to the maximum compressive stress the beam can withstand before buckling (PIP_b).⁽¹²⁾

A second, and less well developed, form of resonant microsensor relies on the effect of the Coriolis force on a resonating structure. Such an effect has been applied in a resonant micro-gyroscope^(13,14) as well as in conventional flow sensors.⁽¹⁵⁾ Figure 4 shows the relationship between the Coriolis force and the resonant sensor's output, which is the amplitude of an induced parasitic vibration.

A third form of resonant sensor relies on the damping effect of the surrounding fluid on the resonator's quality factor (Q-factor). The Q-factor is a figure of merit describing a resonance (see section 4.4). A resonant sensor based upon the Q-factor can act as a viscometer,⁽¹⁶⁾ pressure sensor⁽¹⁷⁾ or vacuum sensor.⁽¹⁸⁾ The use of microresonators will be limited in such applications due to their small dimensions and thus fragility. Figure 5 shows the relationship between a bridge style resonator's Q-factor and the viscosity of the surrounding fluid.

3. Examples of Resonant Microsensors

In the following sections the operating principles of the main types of resonant microsensor are briefly described. More details are given in ref. 1.

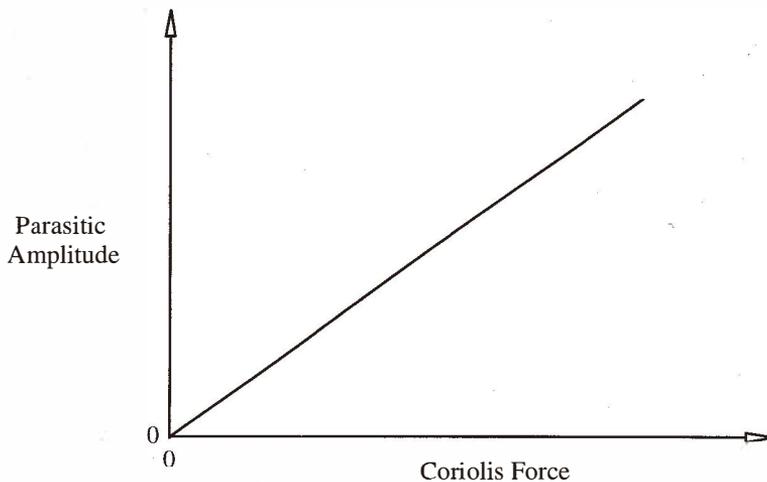


Fig. 4. Coriolis-force-induced parasitic vibration.

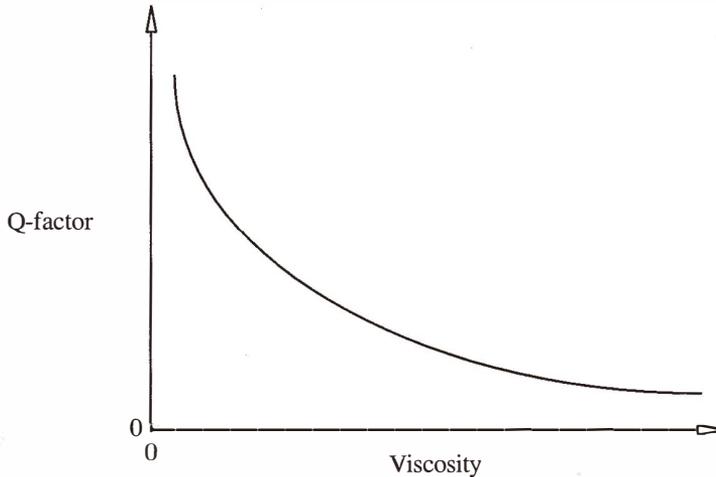


Fig. 5. Q-factor as a function of the viscosity of the surrounding fluid.

3.1 Absolute and differential pressure

Micromachined resonant pressure sensors based on the axial stiffness effect are commercially available. In such devices the resonator is normally isolated from the pressurised medium to avoid density cross sensitivity as well as the influence of other disturbing loads. The resonator is often integrated in, or mounted on, one surface of a diaphragm and maintained in a vacuum to ensure a high Q-factor. The other surface of the diaphragm is exposed to the pressure medium. A pressure difference across the diaphragm therefore causes it to bend thus stressing the resonator and so altering its resonant frequency. Figure 6 shows an early example, now commercially available.⁽⁴⁾ A differential pressure sensor, now also in production, is described in ref. 19.

3.2 Acceleration

Micromachined accelerometers have also been demonstrated based on the stiffness effect but are not yet commercially available. Silicon resonant accelerometers usually consist of an inertial mass supported by one, two or four resonators.^(7,20) Acceleration of the device in its sensitive plane produces an inertial force on the resonators thus altering their frequency. In the multiple resonator version a differential approach can be employed. Acceleration becomes a function of the difference in frequency between the resonators and this reduces sensitivity to cross axis accelerations and temperature. Figure 7 shows an example which uses a single, double-ended tuning fork resonator.⁽⁷⁾

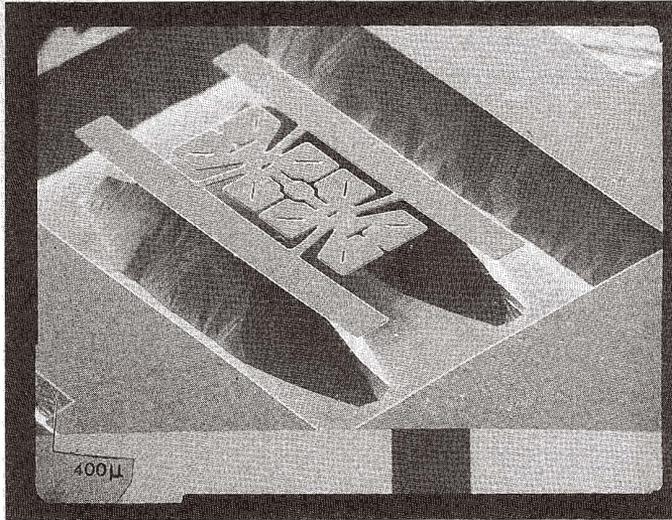


Fig. 6. A micromachined resonant silicon pressure sensor (Acknowledgement is made to Druck Ltd for permission to publish).

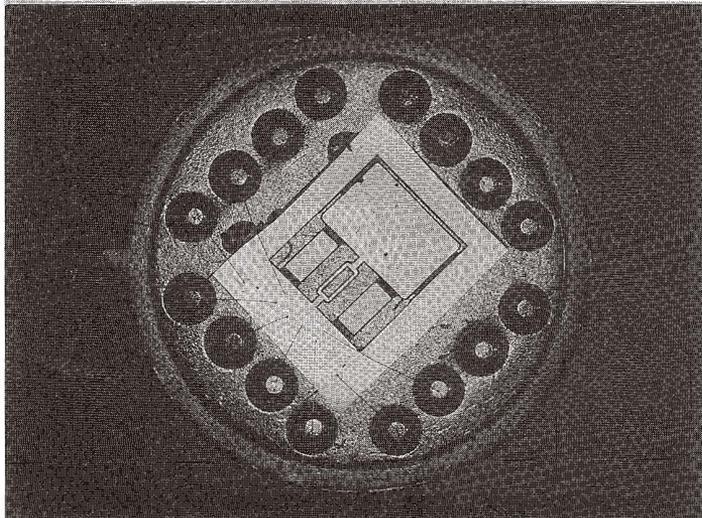


Fig. 7. A micromachined resonant silicon accelerometer (Acknowledgement is made to BNR Europe for permission to publish).

3.3 *Rotation rate*

Finally, the Coriolis-effect-based gyroscope is an important resonant microsensor.⁽²¹⁾ The majority of microgyros to date have been produced in quartz. Such devices consist of a resonator such as a tuning fork vibrating in a high Q-factor mode. Rotation of the tuning fork about its axis induces, by means of the Coriolis force, a second parasitic vibration perpendicular to the driven mode of vibration. The amplitude of the parasitic vibration is proportional to the rotation rate of the resonator.

4. Design Considerations

4.1 *Resonator geometry and mode of vibration*

The fundamental resonator geometries are cantilever beams, bridges and diaphragms. The bridge design, consisting of a single beam fixed at both ends to the surrounding structure, is the most commonly used as it is simple to fabricate and operate. It may vibrate in torsional or flexural modes. More complex resonator geometries offering improved performance characteristics include tuning forks (TF), double-ended tuning forks (DETF), triple-beam double-ended tuning forks (TB) and even quadruple-beam double-ended tuning forks (QDB).^(1,22,23) Such resonators offer dynamically balanced modes of vibration in which the sum of the forces and moments at the supports due to the tine motion is close to zero. This reduces vibration sensitivity and, for vacuum-encapsulated single-crystal resonators, usually results in a high Q-factor and therefore improved sensor resolution.

Balanced modes also offer reduced long-term drift because the surrounding structure does not participate in the resonator's vibrations and so its influence is minimised. Other high Q-factor resonator designs include various plate structures supported at the nodes operating in torsional modes.^(4,24) The resonator in ref. 24 also incorporates an isolating mass structure that further improves the Q-factor of the device. Table 1 gives some examples of resonators which have been fabricated to date.

4.2 *Excitation/detection techniques*

Many techniques have been investigated for the excitation and detection of resonator vibrations. These are described in detail in paper four⁽³⁾ of this special issue and so are not mentioned further here.

4.3 *Importance of nonlinear behaviour*

For a resonating structure the frequency is a function of the square of the amplitude of vibration.⁽³¹⁾ This results from the nonlinear relationship between a resonator's restoring force and its amplitude of vibration. The sign and magnitude of the nonlinearity depend on the resonator geometry, and are particularly influenced by the support conditions. However, provided the vibration amplitude is kept small compared with the radius of gyration of the beam cross section, such effects are negligible.⁽³²⁾ However at large amplitudes a change in amplitude due to, for example, a drift in amplifier gain may cause a significant frequency change indistinguishable from a measurand change. Thus if the device is operated at large amplitudes automatic gain control may be used to reduce this effect.^(4,33) Hysteresis effects⁽³⁴⁾ occur in the resonance curve at even larger amplitudes and therefore resonant sensors are never operated in this regime.

Table 1
Example resonant sensors.

Name/Reference	Function	Structure	Matl.	Process	Drive	Mode	Freq (kHz)	Q (*1000)
Greenwood ⁽⁴⁾	Pressure	Butterfly	Si (p++)	BMM	Electrostatic	T	70	10.00
Howe ⁽²⁵⁾	Vapour	Bridge	Poly-Si	SMM	Electrostatic	F	270.00	—
Ikeda <i>et al.</i> ⁽¹⁹⁾	Pressure	H Shape	Si (p++)	BMM	Magnetic	F	30	50.00
Stachell and Greenwood ⁽⁷⁾	Acceleration	TBTF	Si	BMM	Thermal (resistor)	F	65.00	2.70
Buser and De Rooij ⁽²⁴⁾	Pressure	Plate	Si	BMM	Electrostatic	T	24.00	600.00
Söderkvist ⁽²⁶⁾	Gyro	TF	Quartz	BMM	Piezoelectric	F	37.00	13.7*
Guckel <i>et al.</i> ⁽²⁷⁾	Pressure	Bridge	Poly-Si	SMM	Electrostatic	F	568.00	47.00
Stemme and Stemme ⁽¹¹⁾	Pressure	Diaphragm	Si	BMM+SFB	Electrostatic	F	14.10	2.6*
Söderkvist and Hjört ⁽²⁸⁾	Test	TF	GaAs	BMM	Piezoelectric	T	33.00	27*
Fabula <i>et al.</i> ⁽²⁹⁾	Force	TBTF	Si/ZnO	BMM	Piezoelectric	F	17.60	0.40
Tilmans ⁽³⁰⁾	Strain gauge	Bridge	Poly-Si	SMM	Electrostatic	F	323.70	0.60
Andrews <i>et al.</i> ⁽¹⁷⁾	Pressure	Plate	Si	BMM	Electrostatic	F	20	20-30 (0.01-0.02)*
Burns <i>et al.</i> ⁽⁸⁾	Acceleration	Bridge	Poly-Si	SMM+BMM	Electrostatic	F	500	20

BMM: Bulk micromachined, SMM: Surface micromachined; T: Torsional; F: Flexural; *: at atmospheric pressure.

4.4 Importance of Q -factor

The Q -factor of the mode of vibration is of great importance in resonator design. It must be high enough so that, should the phase of the maintaining electronics drift, the resulting frequency change will be negligible compared with the required overall accuracy and drift requirements. In addition the Q -factor is a measure of the sharpness of the resonance curve and thus determines the sensor's resolution. Finally the Q -factor is inversely proportional to the power consumption of the resonator and thus a high Q -factor is desirable in battery or low-power applications.

The Q -factor is limited by three types of damping mechanism. The most significant mechanism is due to the interaction of the resonator with its surrounding fluid. This can be avoided by operating the resonator in a vacuum (see section 4.7). The energy coupled from the resonator through its supports to its surroundings represents the second most important mechanism and this can be minimised by employing various resonator designs as discussed in section 4.1. The third damping mechanism results from energy dissipated internally within the resonator material.

The Q -factor must not be too high since the amplitude at which hysteresis in the resonance curve occurs, due to nonlinear behaviour, is inversely proportional to $Q^{1/2}$.⁽³⁴⁾ Thus with a very high Q -factor the vibration amplitude may need to be kept very low.

4.5 Influence of maintaining electronics

Maintaining electronics consist of either a simple feedback amplifier or a phase-locked loop circuit. In general the amplifier is used to maintain a fixed relationship between the detected resonator amplitude or velocity and the resonator driving force. At resonance the driving force is in phase with the resonator velocity and leads its displacement by $\pi/2$ radians.⁽³⁵⁾ The bandwidth of the resonance curve is determined by the 45° phase shift points either side of resonance. Thus the bandwidth of the resonance in Hz corresponds to 90° of phase shift. Therefore for a typical Q of 10^5 at 100 kHz, the bandwidth of 1 Hz corresponds to 90° of phase shift. By estimating the expected phase drift of the electronics, one can hence determine the expected frequency drift of the sensor from this source. It can be seen from the above example that a higher Q reduces sensitivity to electronics drift.

4.6 Power consumption

The power consumption in a micromachined resonator is extremely low. It is equal to the energy lost per cycle, E_L which can be evaluated from:

$$E_L = \frac{2\pi}{Q} E_S,$$

where E_S denotes the stored energy which is equal to the kinetic energy when the resonator passes through its centre of motion. The maximum kinetic energy for a clamped-clamped beam is given by:⁽³⁶⁾

$$E_S = 6\pi^2 l \rho w f^2 y_m^2,$$

where ρ is the density, t is the beam thickness, w is the beam width, l is the beam length, f is the resonant frequency and y_m is the amplitude. Inserting typical values for a silicon beam resonator of: $\rho = 2330 \text{ kgm}^{-3}$, $t = 5 \times 10^{-6} \text{ m}$, $w = 40 \times 10^{-6} \text{ m}$, $l = 600 \times 10^{-6} \text{ m}$ and $f = 10^5 \text{ Hz}$ results in E_s equal to $1.66 \times 10^{-10} \text{ J}$ for $1 \mu\text{m}$ amplitude of vibration.

Assuming a Q of 10^5 gives a power consumption of only 10.4 nW , which represents the actual power dissipated by mechanical damping effects on the resonator. The electrical drive energy will be greater than this since no drive mechanism possesses 100% efficiency. In addition, the power consumed by the maintaining electronics and vibration detection mechanism must be considered.

4.7 Encapsulation and packaging

Resonant sensors generally require a reference vacuum around the resonator. This has been accomplished at wafer level using a sacrificial layer technique.⁽¹⁹⁾ Alternatively the resonator may be held in a hermetic can.⁽³⁷⁾ The sacrificial layer technique is sometimes advantageous since the resonators are sealed within a vacuum whilst still in the clean room. This ensures maximum cleanliness and minimises the probability of drift. However the vacuum cavity formed by a sacrificial layer technique has a minute volume and thus must be completely hermetic if a good vacuum is to be maintained throughout the sensor's lifetime.

The chip containing the resonant sensor can be packaged in similar ways to piezoresistive sensors, i.e. using standard materials and headers derived from the integrated circuit packaging industry. If packaging stress is a problem an isolating intermediate layer made of Pyrex or silicon⁽³⁸⁾ can be used. Decoupling zones can be formed within this isolating layer⁽³⁹⁾ or directly on the sensor chip.⁽⁴⁰⁾

5. Material and Fabrication Issues

Single-crystal materials such as silicon, quartz and gallium arsenide exhibit low acoustic attenuation and hence possess very high intrinsic Q-factors.⁽⁴¹⁾ They are available in wafer form with high purity and with few dislocations, which leads to low resonator drift rates.

The development of single-crystal silicon for integrated circuit fabrication has led to its use in micromachined resonator sensors.⁽⁴²⁾ Silicon has a strength comparable to that of steel, is elastic up to fracture resulting in minimal hysteresis and has an acceptable temperature coefficient of flexural resonant frequency of around $-29 \text{ ppm}/^\circ\text{C}$.⁽⁴³⁾ The fabrication technologies used by the semiconductor industry are applicable to micromechanical structures, allowing many resonator designs to be realised in silicon. Unlike quartz, silicon is not piezoelectric and therefore alternative drive and excitation mechanisms need to be incorporated. Silicon is however piezoresistive with a high gauge factor allowing simple detection of resonator vibrations. The use of silicon also offers the attractive possibility of integrating any required circuitry on the sensor chip.

In the case of sensor and electronics integration it is common for the resonator to be fabricated from polysilicon due to the compatibility requirements of the fabrication

processes. Polysilicon has a granular structure, with the material properties being dependent on the crystal orientations of the individual grains and the grain boundaries. The actual properties of thin films vary according to prior surface preparation, deposition conditions and postprocessing steps such as annealing.^(44,45) Very fine grained, even amorphous, polysilicon layers are typically used in micromechanical applications such as resonant sensors. Polysilicon is not piezoelectric, so the excitation and detection mechanisms must be incorporated into the structures, the most common being thermal and capacitive. It exhibits a piezoresistive effect but with a lower gauge factor than the single-crystal form. The stability of polysilicon has been shown to be satisfactory for resonators.⁽²⁷⁾ However ageing characteristics and Q-factors are expected to be inferior to those of the single-crystal material.

Quartz is available either as amorphous fused quartz (quartz glass) or crystalline quartz, the single-crystal form being used in resonator applications.⁽⁴⁶⁾ Crystalline quartz has anisotropic material properties and is piezoelectric, providing a simple means of exciting and detecting resonator vibrations and also allowing the high Q-factor shear modes to be activated. Quartz exhibits superior aging characteristics to silicon and gallium arsenide, and its linear temperature coefficient of frequency is zero for certain modes in certain crystal orientations. The main disadvantages of quartz include the limited machining processes which are available compared to those for silicon and the fact that electronics cannot be integrated in quartz. Furthermore the cost of quartz wafers is significantly higher than that of silicon wafers.

GaAs is the latest material to be considered for microresonator applications.⁽²⁸⁾ Like quartz it is a piezoelectric material and like silicon it has the potential for integrated circuitry. GaAs has anisotropic material properties and exhibits elastic behaviour up to brittle fracture indicating minimal hysteresis. Its intrinsic Q-factor has been reported to be superior to that of silicon,⁽⁴⁷⁾ and its time and temperature stability are comparable. Its disadvantages compared to silicon include increased manufacturing costs, less developed processing technologies, higher temperature coefficient of flexural resonant frequency of -48 to -59 ppm/ $^{\circ}\text{C}$ ⁽²⁸⁾ and lower strength.

The micromachining of silicon is the most highly developed among those of the three materials, benefiting from process developments in the IC industry. Micromachining falls into two categories, bulk or surface machining. Bulk micromachining involves the selective etching of silicon from the wafer using wet chemical or dry beam etchants. Resonators can be formed by etching completely through pre-thinned regions of the wafer. Pre-thinned areas may conveniently be formed by etching a diaphragm from the wafer back. The resonator is then formed on the top surface of the diaphragm by protecting those regions where no etching is required, that is the resonator itself and its supporting structure.⁽⁴⁸⁾

Resonator-based pressure sensors have been fabricated by etching a cavity in the top surface of a diaphragm and bonding a wafer over the cavity. Etching and polishing of this bonded wafer leaves a thin silicon layer over the cavity from which a resonator can be formed by etching right through to the cavity beneath.⁽⁵⁾

Resonators can be also fabricated using etch stops that render selected regions of the wafer insoluble to the etchant.⁽⁴⁾ For example silicon doped with boron at concentrations

exceeding 4×10^{19} atoms/cm³ becomes insoluble to alkaline etchants. This does however cause contraction of the crystal lattice⁽⁴⁹⁾ inducing structural stresses and precludes the fabrication of electronic devices in the doped region.

The level of boron concentration can be reduced by employing electro-chemical etch stops,⁽⁵⁰⁾ whereby etching is halted adjacent to a pn junction when a potential is applied across it. Another process uses a combination of laser milling and anisotropic etching to form resonators with triangular cross section.⁽⁵¹⁾ This laser machining process is used to form parallel trenches in the <110> silicon which are then exposed to an anisotropic etchant that undercuts the middle region, forming a triangular beam.

Surface micromachining⁽⁵²⁻⁵⁴⁾ processes form resonators on the surface of the wafer. This is usually achieved using sacrificial layer technology.⁽⁵⁵⁾ This approach involves depositing and patterning two films, one top of the other, on the wafer surface. The top film will form the resonator whilst the bottom film is the sacrificial layer which is selectively etched leaving the resonator raised above the substrate. The thin films used for each layer and the etchant type must be carefully chosen to ensure that only the sacrificial layer is etched, and care must also be taken to protect the substrate from the etchant.

The advantages of surface micromachining include its compatibility with IC processes and small resonator size which allows a large number of devices per unit area of wafer. Disadvantages include variation in the deposited film's material properties, the residual stresses which are often present in the films and the inherent fragility of such small structures. However a number of devices have recently been demonstrated.^(19,54,56,57)

For quartz or GaAs the fabrication processes are not as well developed as for silicon. Those for quartz are the most restricted due to the lack of any known etch stop mechanism. Wet and dry etching processes are possible and for z-cut quartz wafers the high degree of anisotropy enables thick structures to be machined with near-vertical side walls.⁽⁵⁸⁾ The fabrication of GaAs resonators can be achieved using processes that are similar to those available for silicon.⁽⁵⁹⁾ Selective etch stop techniques, sacrificial layer technologies, wet and dry anisotropic etching and high-strength bonding processes are all available, though to date these processes are more expensive and not as well characterised as the equivalent silicon processes.

6. Cross Sensitivities

6.1 Temperature and time

The origins of a resonator's temperature coefficient of frequency have been discussed elsewhere.^(1,43) In summary, the temperature coefficient is controlled by the vibration mode, the resonator material and any stresses induced by differential thermal expansion of packaging or deposited layers on the resonator.

Resonator frequencies generally change very little with time. The following factors may affect the stability of resonant frequency, assuming environmental effects are kept constant.

6.1.1 *Relief of packaging or fabrication stress*

Stress may be built into a microengineered resonator during its fabrication, for example by boron doping, the deposition of passivating SiO₂ layers over detection piezoresistors, or the fabrication of vacuum sealing caps. It can also be introduced when mounting the sensor chip, for example by bonding on a Pyrex header at high temperature or by epoxy mounting on an alumina substrate. Such stresses will be relieved with time and repeated temperature cycling, resulting in frequency drift.

6.1.2 *Bias sensitivities*

Electrostatic drive of a resonator requires that the ac sinusoidal drive waveform be superimposed on a DC bias. This ensures that the driving force's frequency is the same as the ac sinusoidal drive frequency (rather than double it as is the case if no bias is present). The DC bias affects the resonant frequency causing an offset in the resonator's frequency.⁽⁵⁶⁾ The offset will vary should the DC voltage reference vary. Similar effects occur with other drive techniques.⁽⁵⁷⁾

Detection techniques also involve similar problems. For example, resistive thermal drive causes localized resonator heating resulting in frequency changes as a result of stress and temperature rises. These stresses will change as, in this case, the resistors drift thus causing unwanted frequency drift.

6.1.3 *Changes in material properties with time*

This effect will be small when compared with factor 6.1.1. It results from diffusion of impurities or changes in the crystal structure due to imperfections in the crystal lattice.

7. Conclusions

The high performance of resonant sensors coupled with the low cost of micromachined resonators promises significant market penetration for resonant microsensors.

To date micromachined resonant devices are commercially available for absolute and differential pressure measurement and rotation rate measurement. Resonant accelerometers have also been demonstrated in the past.

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