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Silicon Resonant Pressure Sensors
— A Market Perspective —

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We* examine the current state of micromachined, resonant pressure-sensor technology in the context of its historical development with a view towards its potential for commercial success. In this paper we discuss the following topics: characterization of basic resonant elements, overview of the pressure sensor market, comparison of conventional and silicon resonant sensors, review of resonant sensor devices and applications, introduction to silicon resonant sensors, and a proposed strategy for a significant market penetration by resonant sensors.

1. Introduction

Diverse physical variables require a similarly diversified range of sensors. One author has stated that fifty thousand types of sensor exist for one hundred measurement parameters, an average of five hundred types of sensor for each parameter.(1) Such a large number of sensor types exists as a result of the highly diversified nature of sensor applications, with varying requirements for accuracy, packaging, cost, operating temperature, input-parameter coupling, media protection, regulatory compliance, etc.

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*Authors were cofounders of NovaSensor, a Silicon Valley company that developed and commercialized many MEMS technologies, including a high accuracy resonant pressure sensor. MEMS is defined in the U.S.A. as Micro Electro Mechanical Systems, covering a broad range of mechanical and electro-mechanical integrated circuits. Silicon pressure sensors are so far the most successful commercial applications of MEMS technology.

Pressure and acceleration, the second and third (after temperature) most often measured physical parameters, have been, over the last twenty years, increasingly measured using a single sensor technology—silicon micromachining. During 1970s, silicon was used in only about 10% of all pressure and acceleration sensor applications, currently, over 80% of these applications employ micromachined silicon sensors. Silicon micromachining was the only sensor technology which was capable of delivering both low cost (*e.g.*, \$1.50 for disposable blood pressure sensors(2)), and high-accuracy (*e.g.*, 0.01% for aerospace application(3)).

While silicon technology unquestionably offers the lowest cost pressure sensors, it is still surpassed in accuracy by conventional resonant sensors. Now, after more than a decade of development in university and corporate laboratories,(4) silicon resonant sensors are beginning to enter the marketplace. Initial market entries are in the traditional high-cost, high-accuracy fields including process control, aerospace and secondary standards for instrument calibration.

The next decade will be critical for the commercial success of this technology. The demonstrated accuracy of these sensors, combined with the size, ruggedness and cost advantages of micromachined technology ensure that this technology will achieve, at minimum, limited success in niche, high-accuracy applications. It is less clear whether the technology possesses the potential for the design and production of a range of sensors with price/performance competitiveness to micromachined piezoresistive and capacitive technologies. We believe, and present evidence in this paper, that this potential does exist.

Although this technology can be applied to a broad range of mechanical sensors, we focus in this work on pressure sensors. Pressure sensing is the largest market for sensors, and the one in which resonant micromachined sensors can be expected to achieve significant early commercial success.

2. Resonant Sensor Structures

Resonant sensors convert the physical parameters to be measured into a change in the resonant frequency of a vibrating element. A resonant pressure sensor consists of three essential elements:

- Force collector, which converts input pressure to stress.
- Vibrating element, which responds to the stress in the force collector.
- Driver-detector electronics, which provide energy for maintaining oscillations at resonance, and detect and decode the resonant frequency.

Due to the nonlinear response of this class of sensors, microprocessor-based signal-conditioning electronics are usually employed to achieve high performance calibration, linearity correction and temperature compensation. These electronics may be included in the sensor package, or the function may be performed by another portion of the measuring system.

The resonant frequency of a sensor is a function of the inertial and resistive (or elastic) properties of the resonant member, and the force applied to the element by the force collector. This force is, in turn, a function of the dimensions and elastic properties of the force collector. Many designs for resonant elements have been developed. These include

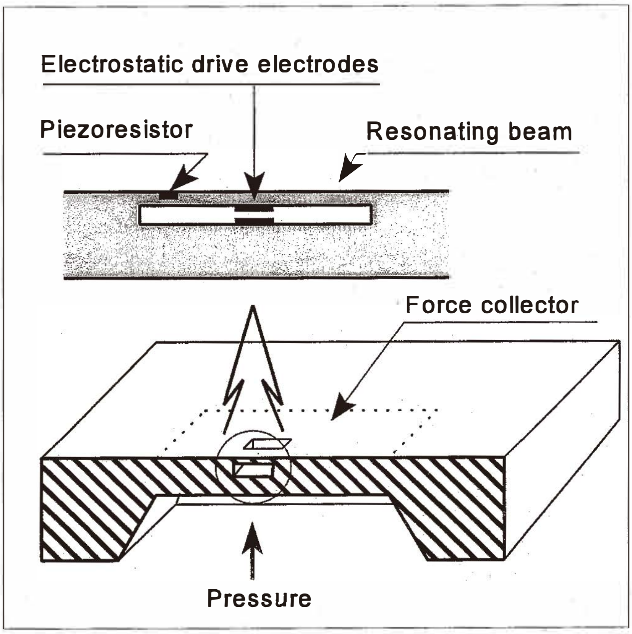

Fig. 1. Simplified structure of silicon resonant pressure sensor. The diaphragm acts as a force collector, converting pressure to stress in a thin beam, which changes the beam's resonant frequency. Oscillations are maintained using electrostatic force electrodes (shown in the enlarged beam cross section). Detection of the resonant frequency is performed by monitoring the resistance of an ion implanted strain gage. To obtain a high Q, either the top of the chip is sealed in a vacuum created in the package, or a vacuum cavity is created directly on the chip around the resonant beam.

vibrating strings, beams, diaphragms, capsules, cylinders, forks and a variety of other designs.

For practical levels of stress, the typical full scale frequency change due to applied stress for a resonant sensor is about 10% to 30%. Typical relative resistance change for piezoresistive sensors is within the range of 1 to 10%.

The relationship between the frequency and applied pressure varies with the design. For simple structures the relationship is straightforward, but for more sophisticated structures it is complex. In general, this relationship is nonlinear. A few examples are discussed below.

2.1 *Resonant frequency of a string*

The resonant frequency f_m of a vibrating string is a function of two dimensional parameters: its diameter and length. The frequency of a given vibration mode m ($m = 1, 2, .., n$) is a function of the stretching force F, and is given by[5]

$$f_m = \frac{m}{l}\sqrt{\frac{F}{\pi d^2 \rho}}, \tag{1}$$

where l is the string length, d is its diameter and ρ is the material density. Multiple resonant frequencies exist, which in this case are harmonics. The relationship between the frequency and the applied force is inherently nonlinear and signal correction is required to obtain a linear output. The sensor zero is dependent on the initial tension in the string. From a manufacturing perspective, the unit-to-unit and lot-to-lot variations of the sensitivity depend only on the tolerance of the diameter and length, given a constant material density, and to a lesser degree, on the pre-tensioning of the string.

2.2 *Beam resonant frequency*

A beam is a modification of a string, and a lack of symmetry complicates the relationship for the resonant frequency. The resonant frequency f_i for flexural vibrations of a rectangular cross-section beam with a large width w compared to its thickness h ($w > 5h$) and subjected to an axial load F is given by(6)

$$f_i = \frac{\alpha_i^2}{2\pi\sqrt{12}}\sqrt{\frac{\hat{E}}{\rho}}\frac{h}{l^2}\sqrt{1 + \mathrm{Y}_i \frac{Fl^2}{\hat{E}bh^3}}, \tag{2}$$

where l is the beam length, α_i and Y_i are constants for a given mode I, ρ is the material density, and $\hat{E}$ is the effective Young's modulus (E). For the narrow beam ($b \approx h$) the effective Young's modulus equals Young's modulus itself. For the wide beam it depends on the Poisson ratio v

$$\hat{E} = \frac{E}{1 - v}. \tag{3}$$

Several resonant modes can be expected. These can result in mode overlap which is highly undesirable, because it results in a nonuniform signal due to mode switching within the operating range of the transducer. Mode overlap of the flexural modes given by eq. (2) will not occur (almost by definition). They may appear, however, as a result of interference with torsional modes and/or flexural modes in the width direction.

2.3 *Vibrating cylinder*

One of the de facto standards in accurate pressure measurement is the vibrating cylinder sensor developed by Solartron. This sensor was developed to measure the altitude and air speed for demanding air data computers in commercial and military avionics. A resonant cylinder has several natural frequencies, each dependent on the applied pressure. The lower frequencies correspond to hoop modes, and the higher frequencies correspond to tangential modes. The relationship between a mode resonant frequency $f_{n,m}$ and pressure P

for the hoop mode (which is more sensitive to pressure) is

$$f_{m,n} = \frac{1}{2\pi a}\sqrt{\frac{E}{\rho}\left(\frac{\lambda^2}{n^2+\lambda^2} + \frac{h^2(n^2+\lambda^2)}{a^2(1-v^2)} + \frac{Pa(\lambda^2+n^2)}{2Eh}\right)}, \tag{4}$$

where a is the internal radius of the cylinder, h is the cylinder wall thickness, ρ is the density of the cylinder material, E is Young's modulus, v is Poisson ratio, and λ is defined as

$$\lambda = \frac{\pi a}{l}\left(m + 0.3e^{-\frac{qh}{d}}\right), \tag{5}$$

where l is the cylinder length, and m, n are integers related to the vibration mode, q is an empirically determined constant, and d is the thickness of the end plates to which the cylinder is mounted.

Depending on the design, the critical dimensions of the cylinder (a, h, l) may be closer to each other than in the case of a beam, making it easier for different modes to overlap within the operating pressure range. Special care must be taken to eliminate this possible mode overlap for the calibration and compensating algorithm.(7)

3. Overview of the Pressure Sensor Market(8)

The pressure sensor market is large and growing, with total annual revenues of about 2.4 billion dollars. This market can be partitioned into six major segments, each with different characteristics, as shown in Table 1.

Many pressure sensor technologies are available. The market shares of various technologies are shown in Table 2. All markets, and particularly the high-volume cost

Table 1
Pressure sensor market.

Market segment	Number of suppliers	Number of customers	Average price	1995 Shipments	Growth rate
Process control	100	5000	$825	$1,000M	6%y
Industrial control	500	20,000	$150	$400M	10%y
Aerospace and military	100	500	$615	$360M	0%y
Automotive	25	100	10	$340M	20%y
Medical	100	500	$20	$250M	6%y
Consumer	20	50	5	$50M	20%y
TOTAL	845	26,150		$2,400M	8%y

Table 2
1995 Market shares of various pressure sensing technologies (units).

Market segment	Sensor technology					
	PiezoR	Cap	SGage	Reson	Other	1995 Units
Aerospace and military	60%	5%	20%	10%	5%	0.6M
Process control	40%	50%	5%	2%	3%	1.2M
Industrial control	75%	5%	15%	0.1%	5%	3.3M
Medical	99%				1%	18M
Automotive	80%	19%			1%	29M
Consumer	100%				0%	2M
TOTAL	86%	12%	1%	1%	0%	54.1M

here: PiezoR: Silicon piezoresistive strain gages
Cap: Ceramic and metal capacitive
SGage: Metal strain gage
Reson: Resonant

sensitive sectors, are already dominated by silicon piezoresistive sensor technology.

The market share of micromachined silicon sensors has grown significantly and is now dominant in terms of both revenue (about 40% of shipments) and unit shipments (86%). In attaining this position, silicon pressure sensors have replaced strain gage technology. The greatest success of MEMS sensors is represented by the first two multimillion unit volume applications:

- automotive manifold pressure sensors, and
- disposable blood pressure sensors.

Today, silicon sensors are rivaled only by conventional capacitive technologies due to the unprecedented success of Rosemount's capacitive process transmitter and the ceramic capacitive pressure sensors for automotive applications developed by Kavlico and Texas Instruments. However, these companies are evaluating(9) silicon for the next generation of products.

3.1 *Resonant sensors*

Recently, resonant-element pressure transducers entered the process control market, and now have established a significant niche in the high-accuracy aerospace and secondary standard pressure measurement market segment. We believe that the best market potential for resonant sensor technology is represented by the following three applications.

- ***Aerospace "High Accuracy"***, where there is already a significant penetration by resonant sensors. The key advantage of resonant sensors for this market is excellent stability which results in a very high measurement accuracy. Two potential advantages for this market which have not yet been commercially exploited include high operating temperature range and radiation resistance.
- ***Process Control***, where high accuracy results in a very high turn-down ratio: the ratio

of maximum to minimum FSO, which can be remotely adjusted within the transducer; *e.g.*, 100 kPa full scale range which can be electronically adjusted to 1 kPa full scale or any range of intermediate value. The optical powering and readout recently demonstrated by Zook *et al.*[10] may provide an additional advantage for this market, as it can be used to simplify the bidirectional overload protection, which is currently provided by machined metal components (*e.g.*, to allow a 10 kPa differential pressure sensor to withstand a bidirectional 30 MPa overload).

- ***OEM***, where resonant sensors are not currently a factor. In this market, resonant sensor technology has advantages such as improved accuracy, direct compatibility with microprocessors, smaller temperature errors to be compensated compared with those for piezoresistive devices, and lower package stress sensitivity than piezoresistive sensors. It also has the potential for using a digital IC process (with rapidly shrinking feature sizes) for the signal conditioning of ASIC to directly provide digital output, as the analog performance is not critical and no A/ D converter (which occupies a largest chip area) is required. This results in a smaller chip size, thus lower cost.

The majority of existing and near-future commercial applications for high-accuracy transducer products corresponds to one of these categories. Table 3 summarizes the key requirements for the successful application of resonant pressure sensors in each of these market segments.

4. Advantages and Disadvantages of Resonant Sensors

4.1 *Advantages of resonant sensors*

Resonant sensors have a number of advantages over most competing technologies. The advantages discussed below are applicable to all resonant sensor technologies.

Accuracy

Resonant sensors have a demonstrated accuracy, which is, arguably, equal to or better than that of primary pressure standards (which are used by national calibration laboratories).

Frequency output

Resonant sensors provide a frequency output, which, when coupled with a very high Q-factor, practically eliminates the errors resulting from the on-chip or off-chip electronics. Similar to primary pressure standards, but unlike piezoresistive or capacitive sensors, the response of a resonant sensor is a function only of its physical dimensions and basic material properties. It is insensitive to parasitic electrical effects (such as leakage current and stray capacitance), and relatively insensitive to electronics offset and gain drift as a result of the high Q-factor and no requirement for a stable DC performance.

Furthermore, a frequency output eliminates the need for an expensive A/D converter which is necessary to couple other sensor technologies to digital systems. Thus, with simple closed-loop sense-drive electronics, a resonant sensor can provide a highly stable microprocessor-compatible output.

Frequency measurements eliminate many restrictions associated with analog measure-

Table 3
Key requirement for successful application of resonant sensors in three market segments.

Item	Market segment		
	Aerospace	Process control	OEM
Minimum pressure range	2.5 kPa (10″ H_2O)	50 kPa with 100:1 turndown	0.25 kPa
Maximum pressure range	100 MPa (15,000 psi)	30 MPa (5,000 psi)	30 MPa (5,000 psi)
Temperature range	– 55 to 150°C	– 40 to 150°C	– 40 to 125°C
Typical package	Stainless steel	Stainless steel	Stainless steel Gold plated Kovar
Static accuracy	0.001% to 0.1%	0.001% to 0.01%	0.01% to 0.1%
Typical applications	Aircraft air data Jet engine controls Pressure calibrators Barometers Weapon systems	Differential process transmitters	Building blocks for transducers Calibrators
Dominant technology	Piezoresistive and resonant	Metal capacitive and piezoresistive	Piezoresistive
Selling prices	\$3,000 – \$5,000	\$500 – \$2,000	\$10 – \$100
Barriers to entry for resonant sensors	Conservatism of users High cost of qualification for critical application	Development cost	Unit cost
Typical suppliers	Honeywell Solartron Druck	Rosemount Yokogawa Honeywell	Lucas NovaSensor EG & G ICSensors Keller

ments, such as Johnson noise or switching noise, and provide significantly better measurement resolution than other sensing technologies.

Ruggedness

Conventional resonant sensors, particularly the vibrating-cylinder sensor, are also highly suitable for extreme and harsh environment aerospace applications since they depend only on the resonant frequency of the vibrating element. Because of its small size and integrated silicon structure, a silicon resonant-element sensor simplifies the complex flexure and counter balances of conventional sensors, improving the durability of the device.

Low inherent temperature errors

The Young's modulus and sensor dimensions change with temperature, resulting in pressure sensitivity temperature errors. For integrated silicon sensors, the resulting temperature errors of sensitivity are of the order of −40 ppm/°C. This compares with errors of −2000 ppm/°C for the pressure sensitivity of typical piezoresistors.

Lower package stress sensitivity than piezoresistors

Piezoresistors respond to a 6-dimensional stress vector. A resonant sensor responds only to unidirectional stress, resulting in improved package stress isolation. This makes stress isolation easier to implement than for piezoresistive sensors, but more difficult than for capacitive sensors. For high accuracy applications, package stress isolation is a critical task.

4.2 *Disadvantages of resonant sensors*

Resonant-element sensors also have disadvantages as compared to other technologies.

Humidity and density sensitivity

Designs that employ a resonant element directly coupled to the input media (such as the vibrating cylinder) are sensitive to humidity and density, due to mass loading of the resonant element.

Complexity

Resonant sensor design is significantly more complex than for most other technologies.

More advanced electronics

To provide a calibrated output, this class of sensors is used in conjunction with a microprocessor complemented by discrete electronics, which provides an additional functionality, but at the expense of increased cost and complexity in comparison to piezoresistive devices. Integration of all electronics on single chip is feasible, but current volumes do not justify it. An interesting aspect of signal conditioning electronics for these devices is that it can be developed using only a "digital" process, thus it can be inexpensive for a high-volume implementation.

Cost

Resonant sensors are relatively expensive due to their high complexity, the need for advanced associated electronics, the relatively expensive calibration required for the niche, and the high-accuracy markets in which they primarily compete.

4.3 *Advantage of resonant sensors*

Silicon resonant sensors offer significant advantages over other resonant technologies, as discussed below.

Predictable materials

Silicon is an excellent material with clear advantages over metals such as invar and stainless steel, which are used in the fabrication of existing vibrating diaphragm, cylinder and wire sensors. Silicon is a single-crystalline material readily available with ultralow dislocation densities. It exhibits little or no inherent creep or hysteresis. It is comparable to quartz, which is employed in several resonant sensors. It is, however, stronger than quartz by a factor of six and its elastic modulus is three times higher.

Silicon is one of the purest materials commercially available; its properties result in consistent mechanical performance, unlike that of many other materials in which micro contaminants affect the long term stability and hysteresis. The hysteresis and stability of metals depend on the residual trace elements and the processing history, and vary from shipment to shipment. To achieve the required high stability, sensor manufacturers have to purchase large quantities of a particular metal several years in advance of production, make sample sensors and test their stability, and then use or discard the material based on the test results.

Small size

Micromachining allows fabrication of very small structures with vibrating sensing elements tightly integrated with the force collector. The resulting small size and weight are important competitive advantages in many specialized aerospace applications such as satellites, missiles, and small jet-engine fuel-management systems.

Low cost and high-volume manufacturability

Small size and batch manufacturing are the two key factors which have resulted in the low-cost and high-volume manufacturability of integrated sensors. The sizes of current resonant sensors are comparable to those of piezoresistive sensors. The manufacturing process is more complex, and the application volumes are significantly smaller, leading to the current high sensor manufacturing cost. However, it is significantly lower than that for the current mechanical resonant sensors.

High resonant frequency

Silicon's high stiffness-to-density ratio, combined with the fact that micromachining can be used to create geometries resulting in higher resonant frequencies (100 kHz to 1 MHZ), as compared to those of conventionally machined metal (5 – 20 kHz) and bending-mode quartz structures (40 kHz), although they are not as high as those of as shear-mode quartz sensors (15 MHZ). High resonant frequencies simplify signal conditioning, and result in a faster response time.

Package stress decoupling

A critical factor in the performance of resonant sensors is decoupling the vibrating element from the package stress. The small size (typically 4 mm square) and low mass (on the order of micro or milligrams) makes decoupling easier than that for conventional vibrating-element sensors.

5. Comparison of Piezoresistive, Capacitive and Resonant Sensors

There are many principles utilized in the design of silicon pressure sensors. Only two approaches, however, have resulted in substantial market penetration: piezoresistive and capacitive. Commercial piezoresistive sensors are based on micromachined silicon diaphragms, and capacitive sensors are based primarily on metal and ceramic technologies. In Table 4, differences between these designs are compared. Few micromachined silicon resonant sensors have been commercially introduced, therefore, this technology is not a significant commercial success.

Some of the key points raised by the comparison in Table 4 are as follows.

- Control of pressure sensitivity is an important consideration in the manufacture of pressure transducers. Since most silicon resonant sensors have a combination of a diaphragm and a resonant member, for practical purposes, production sensitivity variations are comparable to those of piezoresistive pressure sensors. A capacitive sensor, on the other hand, has a pressure sensitivity that is proportional to the inverse cube of the diaphragm thickness and is, therefore, inherently more sensitive to dimensional variations.
- Resonant devices with a sealed vibrating element, as well as piezoresistive sensors, are relatively insensitive to moisture, whereas capacitive sensors respond to the large dielectric constant of water, which is 81 times larger than that of air.
- The design of very low pressure range piezoresistive sensors is limited by factors including the ratio of the piezoresistor junction depth to the diaphragm thickness. The minimum junction depth is constrained in current stable piezoresistive processes to about 1 μm. Resonant sensors have an equivalent restriction due to the ratio of the resonant element thickness to the diaphragm thickness. Capacitive sensors do not have a junction and can employ thinner silicon or much thinner silicon oxide or nitride diaphragms, allowing operation at extremely low pressures. Despite the restriction on diaphragm thickness, the inherent high accuracy and correspondingly large dynamic range of resonant devices makes measurement of very low pressures feasible.
- The stability, especially of low pressure range devices, is also affected by the stress isolation from the package. Piezoresistive sensors respond to all six components of stress in the plane of the diaphragm at the location of strain gages, and therefore, package stress isolation is quite difficult for low pressure ranges and high-accuracy measurements. Resonant sensors respond only to one component of stress, making stress isolation easier. Capacitive sensors, however, which react primarily to the average diaphragm displacements normal and transverse to the plane of the diaphragm, are less sensitive to package stress (as in-plane stresses are usually greatly reduced by a suitable package design).
- The output signal for a piezoresistive sensor is linear and typically in the range of 1 – 10% of the supply voltage. Resonant sensors give a nonlinear change in resonant

Table 4
Comparison of silicon piezoresistive, capacitive and resonant sensors.

Item	Piezoresistive	Capacitive	Resonant
First production	1958 Kulite	1980 Ford	1990 NovaSensor 1990 Druck
Number of Manufacturers	40	10	4
Annual volume	40 million	0.1 million$^{(11)}$	0.040 million
Number of applications	1000+	Limited	Few, emerging
Differential design	Available	Difficult	Available
Pressure sensitivity vs. diaphragm thickness t	t^{-2}	t^{-3}	t^{-2}
Sensitivity to moisture	None	High (between electrodes)	Low
Very low pressure range	Limited	Easier to obtain	Easier to obtain
Package stress sensitivity	High	Low	Medium
Output signal	1–10%	3–25%, nonlinear	10–30%, nonlinear
Direct μP compatibility	No	No	Yes
Signal conditioning	Simple	More difficult	Complex, but digital
Electronics errors contribution	Significant	Significant	Insignficant Reduced by Q
Parasitic capacitance	Not important	Critical	Not important
Uncompensated temperature errors	Large	Small	Small
Demonstrated accuracy	0.02% FSO	0.02% FSO	0.001% FSO
Operating temperature range	150°C junction 300°C for DI, 450°C for sapphire	150°C	600°C potential with optical readout
Micromachining	Easy	Easy	Complex
Typical pressure ranges	7 kPa to 100 MPa	1 kPa to 50 MPa	50 kPa to 50 MPa

frequency of 10 – 30%. Capacitive sensors give a nonlinear hyperbolic output in the range of 5 – 25%. Piezoresistive sensors do not require linearity correction for most applications. The output of capacitive sensors may be linearized using simple analog electronics. Resonant sensors are usually algorithmically corrected using microprocessor-based electronics.

- Signal conditioning for piezoresistive devices is simple, although the analog electronics can introduce temperature and stability errors. For capacitive sensors, the electronics are more complex and inherently sensitive to parasitic capacitance, which is often larger than the sensor capacitance. Most resonant sensors require a complex closed-loop circuit, with drive electronics to lock onto the resonant frequency of the vibrating element, and sense electronics to provide a readout of the resonant frequency. For resonant sensors, electronics errors are significantly reduced as a result of the high Q-factor, which is of the order of 100,000 for silicon sensors, provided that the input circuitry does not load the sensor.
- The piezoresistive effect is inherently temperature dependent, with a temperature sensitivity of the order of –.05 ~.3%/°C, depending on the piezoresistor doping level. The temperature dependence of the pressure sensitivity of capacitive and resonant sensors is primarily related to the relatively small change in elastic modulus and dimensions, enabling design of internally compensated sensors.
- For resonant sensors, the conversion accuracy depends only on the mechanical properties of the vibrating element. It is not dependent on the junction properties or electrical parameters such as the resistance and capacitance, as is the case for piezoresistive and capacitive sensors. While some piezoresistive and capacitive pressure sensors have achieved NIST traceable accuracy of the order of .02%,(3) silicon resonant pressure sensors with .01 ppm short-term stability have been reported. Quartz sensors, however, have been reported to achieve even better performance.(12)
- The maximum operating temperature for piezoresistive devices is constrained either by junction isolation to 150°C or, for dielectrically isolated or sapphire-based piezoresistors, by the contact metal systems to 250 – 450°C. Capacitive sensors have a similar contact metal restriction, which is compounded by the need for either low-capacitance cable, or integrated high-temperature electronics. High-temperature capacitive devices are not commercially available. Resonant structures offer an option of optical readout without any metallization(13) and can thus potentially extend the operating temperature range up to 600°C, the lower plastic temperature limit of silicon. The possibility of optical excitation leads to a wide range of novel commercial applications.

6. Commercial Resonant Pressure Sensors

Resonant pressure sensors employing conventional electromechanical transducer technology have been important in the world pressure transducer market for over fifty years. Naturally, this market is attractive for those who wish to capitalize on the new, potentially superior, micromachined silicon resonant pressure sensor technology.

However, it is advisable to approach this market with a degree of caution. Conventional technologies often offer outstanding performance by incorporating decades of sophisticated fine tuning of the technology into the product characteristics. The higher the transducer accuracy, the longer the exponential learning curve required for the new technology to reach a given performance level.(14)

A one example could be the traditional aircraft cockpit altimeter. Priced at a few hundred dollars, this instrument offers excellent accuracy and ruggedness, combined with a built-in analog/digital display. The materials employed have been extensively developed in order to minimize temperature effects and hysteresis. Sophisticated mechanical trimming compensates for the temperature sensitivity. A field-programmable user interface is included to allow barometric pressure correction. Today, despite thirty years of extensive commercial development, it is still difficult to obtain the price-performance characteristic of this conventional mature-technology-based sensor using a silicon sensor based instrument.

Several commercial resonant pressure transducers have been introduced to the market during the last few decades. These products were developed for four markets: process control, down-hole geophysical, aerospace and secondary standard calibration applications. The common factor and motivation for these developments was the requirement for accuracy not then available using existing technologies, such as strain gage, capacitive or piezoresistive.

Although quite successful in the marketplace, conventional resonant pressure sensor technology has been less visible than competing technologies. This can be attributed to the following factors.

1. Significant technological development barrier.
2. Low-volume applications in slow-growth market segments.
3. Focus on niche, high-accuracy and high-cost applications.
4. Limited and constant number of customers for such products, who are known to resonant sensor manufacturers, thus eliminating the need for marketing activity.

6.1 *Selected electromechanical resonant transducers*

The following review is meant to encompass commercially successful designs; however, it does not cover all designs. Vibrating element pressure transducer designs have been very successful in the aerospace segment, achieving better than 50% market share in the air-data and barometry measurements. The only serious competition has been from metal and quartz capacitive and micromachined silicon technologies produced by manufacturers such as Sperry, Hamilton Standard, Honeywell and Rosemount.

6.1.1 *Resonant cylinder, a reference standard*

The Solartron Transducers Group of The Roxboro Group, Plc in Farnborough, England (until 1994 a division of Schlumberger), manufactures a range of instruments employing an electromagnetically-driven, precision-machined, invar cylinder (see also section 2.3). This technology dates back to the 1950's, and was licensed to Schlumberger by Volvo-Flÿgmotor, where it was developed for aerospace applications. A similar device was also manufactured under license by Hamilton Standard Corp. in Windsor Locks, CT.

The transducer is available in an absolute pressure configuration, with the inside of the sensor evacuated to provide a reference pressure. Differential pressure sensing, which is required for airspeed sensing applications, is accomplished using two absolute sensors, with some decrease in accuracy due to the summation of errors. The transducer resonates in a hoop mode at approximately 5 kHz, operates in the range of –55°C to 110°C, and has a long-term guaranteed accuracy of better than .01%. Both the drive and sense electrodes are electromagnetically coupled to the cylinder.

The stability of these sensors is reportedly better than measurable using the national pressure standards in England.(15) The stability is monitored using a bank of resonant cylinder transducers, which are, in turn, calibrated against the pressure measured in a 2 km hole drilled in the earth.

The resonant cylinder transducer has been very successful in avionic air-data applications, as a secondary standard for bench-top pressure calibrators and in barometric-measurement applications. Because the resonant element is in direct contact with the input media, the device is sensitive to humidity and density. Changes in these variables affect the resonant frequency of the device due to mass loading. These effects, however, are second order and the device has become a standard aerospace instrument.

A typical laboratory-aerospace application is the pressure calibration system used in the high-accuracy calibration of wind tunnels and industrial pressure scanners. Such an instrument might include a silicon piezoresistive, micromachined resonant or other sensor to measure and control the calibration pressures with high accuracy.

6.1.2 *Aerospace designs*

Another sensor in which the force collector and sensor are integrated to form a single

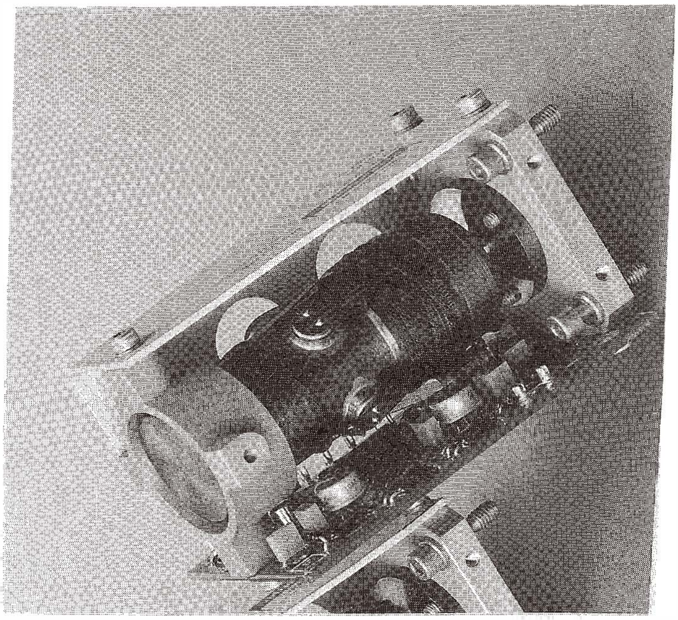

Fig. 2. Vibrating cylinder pressure transducer from Solartron.

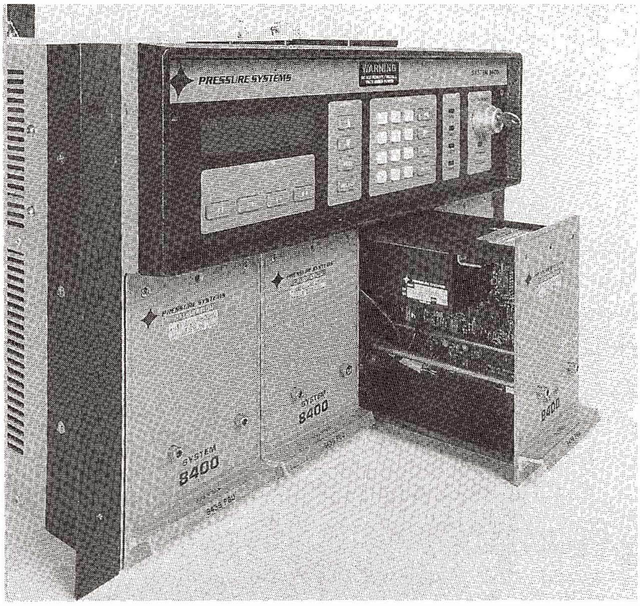

Fig. 3. Typical aerospace laboratory application for high accuracy resonant pressure sensor (courtesy of Pressure Systems, Inc.).

element is the vibrating diaphragm manufactured by the Kollsman Instrument Company. Kollsman has long been associated with aneroid capsule barometers. The company developed an aneroid capsule sensor with a resonant diaphragm which was driven and sensed with electromagnetic coils. A high-accuracy, force balance sensor is described in ref. 16. A conventionally machined piezoelectric resonant-element sensor is described in ref.17. Other conventional resonant sensors are described in refs. 18 and 19.

An alternative approach was used by Paroscientific(20) and Singer-Kearfott. The Paroscientific transducer incorporates a bellows and a relatively massive pivot arm which drives a *macro*machined quartz element. The piezoelectrically active quartz element is both a driver and a sensor. The quartz element is operated in vacuum and can have a Q-factor of up to 40,000.

Since the sensing element is isolated from the pressure media, the device is sensitive to neither density nor humidity. These advantages are obtained, however, with increased mechanical complexity due to the introduction of pivots and linkages. The use of two bellows allows the transducer to function as a true differential unit.(17) However, this is obtained with greater mechanical complexity.

A bellows pivot-arm design was also employed by Rosemount Aerospace Division,(21) which is now part of B. F. Goodrich, USA. The 1501AT high-accuracy air-data sensor incorporated an electromagnetic drive and pickup. Static errors of .025% and a one-year stability of .025% were obtained with this design. A similar design was employed by

Crouzet in Valenze, France, who used a bellows pivot-arm and quartz-resonator design in their Type 51 Smart Sensor.

Recently, Druck, England, and Solartron, England, introduced transducers based on silicon resonant sensors for the aerospace and calibration markets. (Solartron's design is based on the Lucas NovaSensor resonant sensor die.)

6.1.3 *Process control designs*

Another field of application for resonant sensors is that of process-control pressure transmitters. One typical application is high-line-pressure low-ΔP high-accuracy process-control transmitters which can be used to measure 10 kPa (a few-psi) of differential pressure with an accuracy of .1% of full scale output superimposed on line pressures as high as 30 MPa (5000 psi). The pressure range is typically adjusted (turned down) by a factor of up to 400:1. Thus, a maximum range of 100 kPa (400"H_2O) could be electronically amplified to 250 Pa (1"H_2O) full scale. If a .1% accuracy is to be maintained over the entire turn-down range, the transducer must be compensated with a ppm level accuracy (.1% ÷ 400 = 2.5 ppm). The transducer must operate over a wide temperature range in the harsh physical environment of a process control plant.

One of the first applications of resonant pressure sensors in the process control field was the Foxboro 821/823 family of pressure and differential pressure transmitters introduced in the late 1970s. The sensor design consisted of a metal vibrating wire stressed by the differential pressure applied to metal isolation diaphragms. Vibrating wire technology has been shown to be a strong competitor in this market. The Foxboro product achieved excellent performance, but at a higher price than competitive products from Rosemount (metal capacitive sensor) and Honeywell (silicon piezoresistive sensor). Despite the excellent performance of this technology, the market is currently dominated by Rosemount (45% market share) and Honeywell (20% market share). The next-generation resonant ribbon design was not marketed commercially.

In the 1990s, Yokogawa (now Johnson-Yokogawa Corporation) introduced a process control transmitter based on the DP-Harp silicon resonant sensor. This sensor has two locally encapsulated resonators attached to a diaphragm. The resonators are H-shaped and located in the magnetic field produced by a permanent magnet. When current is supplied to one segment of the resonator, the resonator oscillates. This oscillation is detected by the other sensor segment, which generates an emf, which, after amplification, is used to maintain the oscillation.

6.1.4 *Downhole-designs*

Another important application of conventional resonant pressure sensor technology has been in down-hole geophysical measurements in the oil industry. This is one of the most demanding application fields due to the combination of high pressure (over 60 Mpa), requirement for high accuracy (.01%) and high operating temperature (over 200°C). Most sensor technologies cannot be used under these conditions, due either to continuous sensor drift or catastrophic failure.

Typically, the transducer is mounted at the bottom of a drilled oil well. The well is sealed off, resulting in a gradual pressure buildup. Over several days a small change in pressure must be resolved, typically 70 kPa, superimposed on the static pressure of 70 MPa. This change carries critical information regarding the yield of the well and the ratio of the natural gas to oil. A .01% accuracy of the full pressure measurement delivers only a 10% accuracy of the pressure change.

Hewlett Packard in Santa Clara, CA,(22) developed an outstanding product which was, for several decades, the standard for the oil industry. Introduced in 1969, the transducer included a precision-ground quartz cylinder, the resonant frequency of which changed as a function of pressure. The device was supplied as a sensor with calibration coeffficients and an in-line, signal-conditioning module. Although only several thousand devices have been produced over the last two decades, the market was substantial since the list price was $29,000.

7. Silicon Resonant Sensors

The last decade has seen increased interest and rapid development in the area of silicon micromachining. One of the focuses of this effort has been the development of resonant sensors. Thanks to the efforts of many investigators at a dozen or more universities, research institutions and commercial organizations, significant progress has been made. This work resulted in the introduction of the first commercial silicon resonant sensors. However, most of the designs are still in the R & D phase.

Paradoxically, although resonant-element sensors represent the furthest advance of current sensor technology, they were among the earliest fabricated micromachined devices.(23,24) Nathanson's work was particularly important, because it influenced early micromachining investigators. He employed a gold-plated metal cantilever as a resonant element in the gate of a MOS transistor to produce an electromechanical filter with a frequency of 5 kHz and a Q-factor of 500.

7.1 *Pacing the progress*

Many developments mark the progress of resonant sensors. One of the significant factors that influenced the design of resonant sensors was the surface micromachined polycrystalline resonant beam technology developed by Muller and Howe and their team at UC Berkeley.(25,26) A unique resonant pressure sensor developed by Greenwood and others at STC in the UK,(27) was used in the aerospace and calibration markets.(28) Work by Zavracky at Foxboro(29,30) targeted a replacement for process control vibrating wire sensors.

A novel, encapsulated single-crystal silicon pressure sensor for use in process control transmitters was developed by Ikeda and others at Johnson Yokogawa Electric Corporation.(31) This transducer uses dual electromagnetically driven beams mounted on a diaphragm encapsulated in a silicon vacuum reference chamber. This transmitter offers the best commercial performance currently available in process control market.

Petersen and others at NovaSensor developed a novel vibrating element pressure sensor based on silicon fusion bonding, a technique that was exploited extensively at NovaSensor for the development of a variety of micromachined sensors.(32) A new generation of the Solartron resonant sensor was developed using NovaSensor silicon die.(33 – 36)

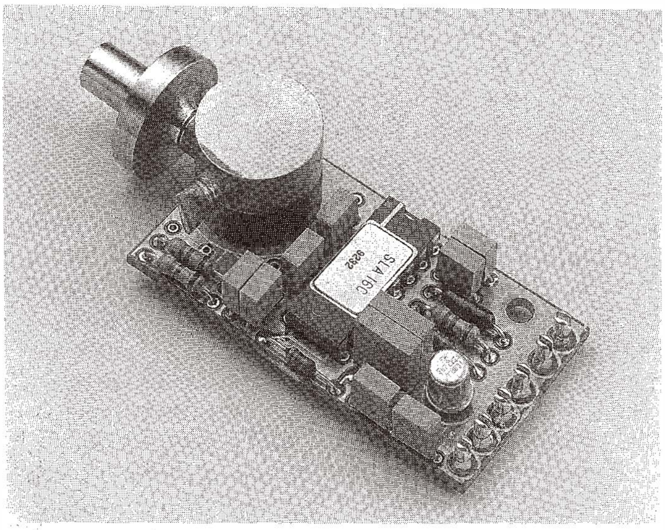

Fig. 4. Resonant silicon beam aerospace pressure transducer from Solartron based on a silicon sensor from Lucas NovaSensor.

More recently, Guckel at Wisconsin University and Burns at Honeywell reported a high-accuracy, differential-pressure sensor based on surface micromachining with a sealed resonator which enabled high-performance differential measurements. The device has demonstrated sub-ppm, short-term stability, and ppm-level long-term stability.(37)

In a significant body of work by Tilmans at the University of Twente,(18) resonant sensor technology developments were systematically analyzed and characterized.

These and other studies by many investigators have resulted in the development of a technology framework ripe for commercial exploitation, with the most attractive results summarized as follows.

1. High-volume silicon resonant sensor die cost is low:

—Small geometries of resonant silicon sensors have been demonstrated. Die sizes are comparable to those of piezoresistive and capacitive sensors, but deliver performance comparable to the large conventional resonant sensors.

—The manufacturing process for resonant sensors is only slightly more complex than that of high performance piezoresistive sensors, *e.g.*, it requires about four more masking steps.

2. The cost of smart sensors with digital output is relatively low.

—Smart transducers with digital output based on resonant sensors do not require the expensive A/D converter required with piezoresistive sensors.

—Increase in resonant sensor die cost (compared to that for capacitive and piezoresistive sensors) will probably be lower than the cost of the high performance A/D converter required for other types of sensors.

3. Single-crystal and polysilicon resonant sensors have proved the feasibility to deliver very high accuracy and stability on the order of 100 ppm/year, which is on par with mechanical counterparts.
4. Several techniques for fabricating hermetically sealed, vacuum reference cavities on the sensor chips have been demonstrated. This allows the design of very high-Q mechanical sensors for differential pressure sensors.
5. Stress-isolation techniques were developed so the stresses from both the internal sensor layers and the package can be effectively controlled.
6. In most resonant sensor designs, the resonant member is hermetically sealed and separated from the force collector, eliminating the sensitivity to density and humidity exhibited by some of their electromechanical counterparts.

The present status of resonant sensor technology can be compared to the status of piezoresistive sensor technology in the mid-1970's. In the commercialization phase that followed the initial developments, piezoresistive sensors competed primarily with more expensive strain-gage pressure transducers in order to gain a foothold in the market. To achieve commercialization of resonant sensors, however, competition from lower cost, previously established and developed silicon piezoresistive technology must be overcome.

There are many barriers to the commercialization of resonant sensor technology. These include the validation of high-volume manufacturing processes, the achievement of consistent stability, as well as mechanical and thermal hysteresis over an extended temperature range, the development of further-improved and lower-cost stress-isolation technology, improved media-isolation technology and the reduction of unit cost.

7.2 *Marketing considerations*

The first commercial applications of micromachined resonant sensors were in the high-accuracy market. They entered the marketplace in direct competition with conventionally produced, large resonant sensors, which had excellent, established, reliable technologies at a mature stage of product development and production.

Notwithstanding the enthusiasm of design engineers towards new technology, the end user is indifferent to the technology employed to solve his problem. Resonant sensors must therefore compete on their own merits. A new product technology can gain customer acceptance by implementing one of the following three strategies.

1. Displacing existing products by offering a better price and/or performance.
2. Expanding the available range of applications.
3. Enabling new applications.

The existing market for pressure sensors is growing, but it is diverse and fragmented. Resonant silicon transducers initially entered this market by offering lower cost for existing, high-accuracy applications. They have potential, however, to provide benefits not currently available from their conventional counterparts, such as:

- More accurate pressure measurements at prices comparable to those of standard transducers.
- Direct digital output at no additional cost.
- On-chip integration of electronics.

- On-chip integration of mechanical functions, such as the bidirectional overload protection.
- Reduced number of components, resulting in improved reliability.

Traditionally, new technologies have found an easy entry into the pressure sensor market when offering such advantages. Suppliers attempting to enter the high-accuracy market with micromachined resonant sensors have competitive advantages, but also some disadvantages. The advantages are:

- The new products may be offered at a price of \$1000 to \$2000. This is below the current price of high-accuracy products which range from \$2000 to \$5000.
- Size is likely to be 25 to 50% smaller than that of the existing products. With small size comes ruggedness. This is particularly advantageous for applications such as on-board jet-engine diagnostics and control.
- Accuracy is likely to be comparable to that of conventional high-accuracy sensors. Although current silicon technology is not as accurate as the most accurate electro-mechanical transducers, it is expected to ultimately result in products with higher accuracy as the technology matures.

The expected major disadvantage is:

- Customers in the air-data and jet-engine control sectors are conservative, and qualification times are long and expensive. The established suppliers will have a clear advantage. Such suppliers who adopt silicon resonant sensor technology are likely to phase in the product slowly in selected applications to avoid cannibalizing their existing market.

The expected first large application for resonant silicon pressure sensors will probably be in the instrument-grade transducer market sector. Present transducers in this segment compromise the required accuracy, particularily over an extended temperature range, in order to meet cost and size requirements. Typical aerospace applications include altitude pressure measurements (*e.g.*, in a cruise missile) and propellant-fuel pressure measurements (*e.g.*, in a rocket).

The last market segment to be penetrated will probably be the OEM marketplace. This sector is, by far, the most difficult due to cost considerations. Resonant sensors are larger and more complex than the piezoresistive sensors which dominate this market segment.

The OEM sector, however, is one in which the emergence of a high-volume application for resonant pressure sensors is feasible. Such a development could make this new technology a market leader. An analogy is the emergence of the requirement for the manifold absolute pressure transducer in the late 1970's that promoted the development of low-cost, piezoresistive pressure sensors which are currently manufactured at a rate of 25 million units/year. Such a high-volume application, which could be in the aerospace, process or automotive market, would result in a production volume necessary to bring the unit cost to a level comparable with that of competing technologies. The specific details of such applications are hard to predict, but they are likely to emerge over the next decade.

It can be expected that the resonant sensor technology will gain a significant market share over the next five years. We further expect it to become the dominant technology for high-accuracy measurements over the next ten to fifteen years.

8. Feasibility of Market Conversion to Micromachined Resonant Sensor Technology

Resonant sensors, while representing the most accurate known silicon sensing technology, have so far not achieved large market penetration, being restricted to the high-accuracy niche market. We believe, however, that resonant sensors have the potential to dominate the market for pressure and acceleration sensors in a manner similar to piezoresistive sensors.

The emergence of low-cost piezoresistive pressure sensors and ICs has increased the volume of sensors by about one order of magnitude per decade, over the last thirty years.(38) The pace was initially restricted by both the development of the technology and the growth of the market.

When piezoresistive sensors entered the market, the total market size was much smaller than it is today. Resonant sensor technology therefore has a major advantage—a much larger total available market (TAM). The existing piezoresistive sensor technology is excellent, and there must be a compelling reason for customers to switch to a new product. Once they have switched, however, the conversion rate from other technologies to resonant sensors could be much faster. We believe that a resonant sensor market volume growth rate of 30 times per decade (41%/year) is feasible during the next twenty years.

Now we discuss a strategy that can help to accelerate the growth of acceleration sensor market. Commercial implementation barriers for introduction of new technology can be divided into several generic categories.

Business strategy

New products cannibalize (replace) old products, creating a strategic problem for existing suppliers. Despite the clear advantage of experience and an established customer base, an existing supplier usually will allow competitors to introduce a new technology to replace its products.

Financial risk

The introduction of a major new technology is expensive, time-consuming and risky. Few sensor companies possess the financial strength, the desire and the determination to successfully undertake such a risk.

Industry support

In contrast to basic semiconductor technology, resonant sensor technology has relatively limited R & D support from the mainstream industry. Developments must be made with the limited resources of sensor R & D centers and companies.

R & D to production transition

The technology has, so far, been developed at advanced R & D centers around the world, without a focus on manufacturability. A transition from an R & D environment to high-yielding low-cost production is slow and expensive.

Die Cost

High-volume piezoresistive sensors have die sizes of 1 × 1 mm fabricated using 6 – 8 masks. To become a mainstream high-volume application, resonant sensor technology must have a comparable die size and process complexity.

Die yield

Piezoresistive sensors are usually made with overall production yields of over 90%. Resonant sensors have been developed using a variety of processes that, so far, have not been validated for high-volume production. A significant effort will be required to develop new resonant sensors with designs that give equally high yield when manufactured on a production line without employing highly qualified personnel.

Ease of signal conditioning

Signal conditioning for piezoresistive sensors is simple and inexpensive, unlike the current generation of resonant sensors. Advances in ASIC technology, however, allow the integration of sophisticated electronics onto a single low-cost (digital CMOS) chip, thus reducing the cost of the electronics for high volume applications.

On-chip integration

Selected high-volume piezoresistive sensors are offered with on-sensor-chip integrated electronics. Resonant sensors will have to follow this path as well.

Even after the cost of resonant sensor technology is brought on a par with that of piezoresistive technology, there still needs to be compelling reasons for users to switch to the new technology. Fortunately, there are several factors in favor of resonant sensors. These factors include the following.

Direct digital output

Resonant-sensor technology is the only one that enables the development of low output level (no built-in amplification) sensors directly compatible with digital systems. Such sensors could be tested by the manufacturer, and then combined with a signal conditioning circuit made by the sensor user. The sensor performance would not be affected by parasitic capacitance or resistance. Currently, however, the market for such sensors does not exist and would have to be created by a dedicated company.

Drive towards a total error band

The imperfections of various sensor technologies and the desire to emphasize the best aspect of each technology has resulted in an elaborate terminology for defining sensor performance. Typically, the sensor manufacturer provides specifications including information on nonlinearity, repeatability, hysteresis, temperature coefficient of offset and sensitivity, thermal hysteresis of offset and sensitivity, temperature coefficient of pressure nonlinearity, nonlinearity of temperature coefficients, short and long term stability, and vibration sensitivity. To understand and properly use this terminology requires years of experience. A reasonable error-band specification is difficult to achieve with current products.(39) Manufacturers claim accuracies of .1%, but deliver total error bands of several percent, even over a modest temperature range.

New sensor users in markets such as automotive and consumer sectors do not want to learn the intricacies of sensor terminology. They want to use sensors in the same way as any other electronic or mechanical component, and not wanting to know all error components used currently in defining sensor performance.

Due to the very high accuracy of resonant sensors, it is feasible to introduce a family of products characterized by a single error: the total error band that would include all error components. This differentiation would be attractive to a broad range of customers, and would allow different classes of accuracy, *e.g.*, 2% for the low-cost market and .01% for the high-performance market. The major differences between these products would be the die size, stress-isolation technique, packaging and testing.

Demand for increased accuracy

Many control applications are required by the government to have improved efficiency, reduced environmental pollution, and increased safety. In response, manufacturers of automotive and factory automation systems introduce more advanced solutions, demanding in turn an increasingly higher sensor accuracy. Resonant sensors can take advantage of such requirements.

No temperature testing for less demanding applications

As discussed before, resonant sensors can provide very low temperature errors, at less than 1%/100°C, without the current mandatory (for this accuracy level) multi temperature testing. This results in a lower cost, and thus, a more competitive sensor.

Emergence of a smart sensor market

The smart sensor market is the fastest growing segment of the transducer market. This market emerged in 1983, and grew to about $500 million in just one decade. The majority of the products in this market sector still provide analog output, which is often complemented by digital ranging and control, and sometimes with a digital output signal. Resonant sensor technology provides simpler interfacing with microprocessors, and thus has an advantage for this high-growth application .

Emergence of distributed sensing and control(40)

Control networking is the newest trend in measurement and control applications. Instead of a rigid hardwired configuration, control networking enables all sensors, controllers and actuators to be connected to a single cable running through the installation, and thus, is a software-based (programmable) configuration. This type of system architecture results in significant reduction of installation costs and acceleration of system design and commissioning. The digital-output compatibility of resonant sensors makes them ideal for such applications.

Demand for increased reliability and diagnostics

The general trend in many industries is towards implementing on-board diagnostic systems that constantly monitor the operation of systems and report problems that require maintenence.(41) Since such systems are based on microprocessors, resonant sensors could provide an advantage.

8.1 *Sample strategy for a resonant sensor startup*

We believe that existing companies may not be willing to fully commit to the development and introduction of resonant sensors because of their commitment to existing technologies. Therefore, the most successful strategy for bringing resonant sensor technology to the market might be through a dedicated startup company or a dedicated new division of a large company. A brief sketch of one possible strategy for such an enterprise is given below.

Founding team

The founding team would include the following key personnel.

1. CEO with a track record in developing a viable sensor company.
2. Resonant-sensor technologist, ideally with a track record in bringing similar products into production.
3. Sales manager with a good understanding of related applications and markets.
4. Operations manager/manufacturing automation expert capable of developing the required high-volume production infrastructure.

Markets

The business would target existing markets for high-accuracy sensors and the fastest-growing smart sensor OEM market sectors in the process, industrial controls and aerospace markets.

Applications

The initial high-accuracy products would fit into the existing sockets in air-data and secondary-standard, pressure-calibration and process control transmitter applications. The basic products would be a header-based OEM sensing module and a 2 cm (.75") diameter transducer in a stainless package with integrated microprocessor-based signal conditioning. The product would be intended to replace the presently dominant semiconductor and thin-film technologies used in these applications. The price would be $400 – 600 for typical aerospace quantities of a few hundred to thousands.

Location

Easy access to world-class universities with a strong technology and financial infrastructure will be crucial. Silicon Valley is still an ideal location, despite the relatively high cost of living. It currently houses thirty-three silicon-micromachining related companies,(42) providing a pool of potential employees. The area has an outstanding IC support infrastructure minimizing the necessary investment in facilities and equipment.

Time frame

The business should achieve profitability in the third year of operation and reach the

$100 million sales level within ten years.

Capitalization

The initial required capitalization would be of the order of $5 –10 million, with a follow-up equity investment of an additional $5 –10 million required in the third year of operation.

9. Conclusions

Silicon resonant pressure sensors are at the beginning of their life cycle. There exists a surfeit of available technology ripe for commercial exploitation. The factors driving market development are similar to those which drove that of micromachined piezoresistive sensing technology in the period from 1975 to the present.

It is apparent that:

- Conventional resonant-sensor technology has a well-deserved, if not widely recognized, niche in the high-accuracy pressure measurement market.
- Silicon resonant transducers offer accuracy which is higher than that of piezoresistive and capacitive sensors, and comparable to that of conventional quartz and mechanical resonant sensors.
- Their small size and ruggedness make them attractive for many applications.

It is less obvious, but arguably true, that:

- This technology can compete with micromachined piezoresistive sensing in terms of cost in high-volume, low-cost, OEM applications.
- This technology is poised to become the dominant pressure transducer technology of the next decade.

The next five years will set the stage for the future development of this technology. A few key decisions made now by existing companies and sensor startup companies will be critical in determining the relative success of this technology over the next several decades.

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