

1

Introduction

A radical change in the entire field of electronics began in 1947 when the transistor was invented; 11 years later in 1958 the first integrated semiconductor circuit was built. Ever since, electronics has turned almost completely into semiconductor electronics. Microelectronic manufacturing methods make it possible simultaneously to produce large numbers of similar components with dimensions that are much too small for precision mechanics. The discovery of the piezoresistive effect in 1953 (Figure 1.1, Table 1.1) created the precondition for also applying semiconductor materials and microelectronic production methods to non-electronic components. The first description of how to use a silicon membrane with integrated piezoresistors as mechanical deformation body dates back to 1962.

Uncountable, new miniaturized function and form elements, components and fabrication procedures have since been introduced, combining electrical and non-electrical functions and using semiconductor production technologies or even especially developed microtechnologies (Figure 1.2).

PHYSICAL REVIEW

VOLUME 94, NUMBER 1

APRIL 1, 1954

Piezoresistance Effect in Germanium and Silicon

CHARLES S. SMITH

Bell Telephone Laboratories, Murray Hill, New Jersey

(Received December 30, 1953)

Uniaxial tension causes a change of resistivity in silicon and germanium of both n and p types. The complete tensor piezoresistance has been determined experimentally for these materials and expressed in terms of the pressure coefficient of resistivity and two simple shear coefficients. One of the shear coefficients for each of the materials is exceptionally large and cannot be explained in terms of previously known mechanisms. A possible microscopic mechanism proposed by C. Herring which could account for one large shear constant is discussed. This so called electron transfer effect arises in the structure of the energy bands of these semiconductors, and piezoresistance may therefore give important direct experimental information about this structure.

INTRODUCTION

THE effect of pure hydrostatic pressure on resistance has been extensively studied, notably by Bridgman, who also made the first piezoresistance measurements¹ known to us on several polycrystalline

from two to six are reported for pressure experiments,⁹ these values agree fairly well for a number of metals with a simple calculation⁹ of the change of mobility produced by the change in the amplitude of thermal vibrations with volume v ,

Figure 1.1 Publication by CHARLES S. SMITH regarding the discovery of the piezoresistive effect in the semiconductors germanium and silicon (*Physical Review* 94 (1954), pp. 42–9). Reproduced by permission of the American Physical Society

Table 1.1 Milestones of the development of microsystem technology (selection) [GERLACH05]

Year	Event
1939	pn-junctions in semiconductors (W. SCHOTTKY)
23-12-1947	Invention of the transistor (J. BARDEEN, W.H. BRATTAIN, W. SHOCKLEY; Bell Telephone Laboratories, Nobel Prize 1948)
1953	Discovery of the piezoresistive effect in semiconductors (C.S. SMITH; Case Institute of Technology and Bell Telephone Laboratories, respectively)
1957	First commercial planar transistor (Fairchild Semiconductor)
1958	Production of the first integrated semiconductor circuit (J.S. KILBY; Texas Instruments, Nobel prize 2000)
1959	First planar silicon circuit (R. NOYCE; Fairchild Semiconductor)
1962	Silicon wafer with integrated piezoresistors as deformation bodies (O.N. TUFTE, P.W. CHAPMAN, D. LONG)
1965	Surface micromachining: resonant acceleration sensitive field effect transistor (H.C. NATHANSON, R.A. WICKSTROM; Westinghouse)
1967	Anisotropic deep etching in silicon (H.A. WAGGENER and his team; R.M. FINNE, D.L. KLEIN)
1968	Development of anodic bonding (D.I. POMERANTZ)
1973	Integration of silicon pressure sensors with bipolar signal processing electronics (Integrated Transducers)
1974	First mass production of pressure sensors (National Semiconductor)
1977	First silicon piezoresistive acceleration sensor (L.M. ROYLANCE, J.B. ANGELL; Stanford University)
1979	Microsystem on a silicon wafer: gas chromatograph for air analysis (S.C. TERRY, J.H. JERMAN, J.B. ANGELL)
1983	Pressure sensors with digital sensor signal processor (Honeywell)
1985	Development of the LIGA technology (W. EHRFELD and his team)
1986	Development of silicon direct bonding (M. SHIMBO and his team)
1988	Commercial application of silicon direct bonding: 1000 pressure sensors on one 100 mm Si wafer (NovaSensor)
1988	Freely movable micromechanical structures (R.S. MULLER as well as W.S.N. TRIMMER and their teams)
1991	Market volume of micropressure sensors exceeds 1 billion US\$
1992	Near-surface micromachining: SCREAM process (N.C. MACDONALD; Cornell University, Ithaca)
1993	Projection display: 768 × 576 mirror array (Texas Instruments)
1994	First commercial acceleration sensor in surface micromachining (Analog Devices)

The term ‘microsystem technology’ has been used for a wide range of miniaturized technical solutions as well as for the corresponding manufacturing technologies and it has no universally acknowledged definition or differentiation.

Similar to microelectronics, the nonelectric domain uses the terms micromachining/micromechanics, microfluidics or microoptics. Until the mid-1980s, the main focus of research and development was on miniaturized sensors, occasionally also on microactuators. Only after that were examples of complex miniaturized systems, such as micromechanical systems (MEMS) or microsystems, in general, introduced (e.g. gas chromatograph, ink-jet nozzles, force-balanced sensors, analysis systems).

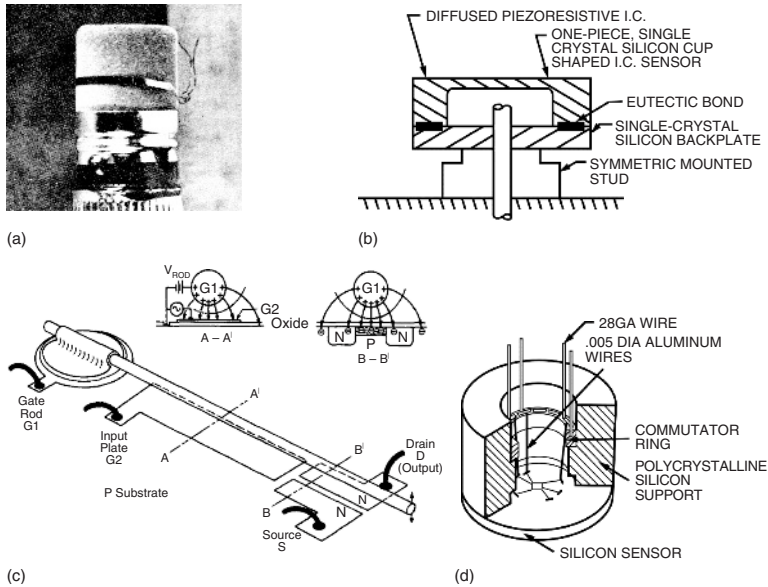


Figure 1.2 Early microsystems: (a) piezoresistive silicon wire resistance strain gauge, wrapped around a pencil (Micro Systems, approximately 1961). (b) integrated piezoresistive pressure sensor. (c) first micromechanically produced surface acceleration sensor (through accelerating a displaced cantilever as a gate of a field effect transistor). (d) pressure sensor with a diffused resistance structure in a single crystalline silicon plate.

(a) Reproduced from Mallon, J. R. Fiftieth birthday of piezoresistive sensing: progenitor to MEMS. <http://www.rgrace.com/Conferences/detroit04xtra/mems/memvent.doc>

(b) Peake, E. R. *et al.* (1969) Solid-state digital pressure transducer. *IEEE Trans. Electron Devices* 16, pp. 870–6. Reproduced by permission of © IEEE

(c) Nathanson, H. C., Wichstrom, R. A. (1965) A resonant gate silicon surface transistor with high-Q band-pass properties. *Applied Physics Letters* 7(4), pp. 84–86. Reproduced by permission of American Institute of Physics

(d) Kotnik, J. T., Hamilton, J. H. (1970) Pressure transmitter employing a diffused silicon sensor. *IEEE Transactions on Industrial Electronics* IECI-17(4), pp. 285–91. Reproduced by permission of © IEEE

1.1 WHAT IS A MICROSYSTEM?¹

This book will use the term ‘microsystem technology’ to mean the following:

Microsystem technology comprises the design, production and application of miniaturized technical systems with elements and components of a typical structural size in the range of micro and nanometers.

A microsystem can be characterized by the semantics of its word components ‘micro’ and ‘system’:

- Components or elements of microsystems have a typical size in the submillimeter range and these sizes are determined by the components’ or elements’ functions. In general,

¹Portion of text is reproduced by permission of The American Physical Society.

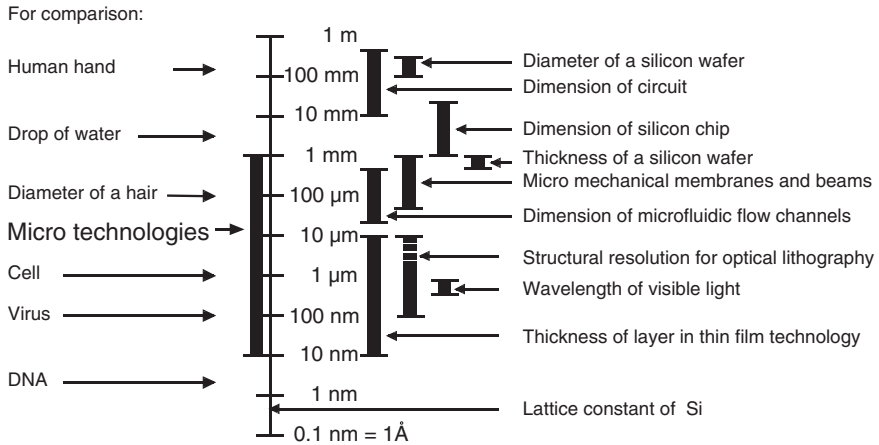


Figure 1.3 Dimensions in microtechnology

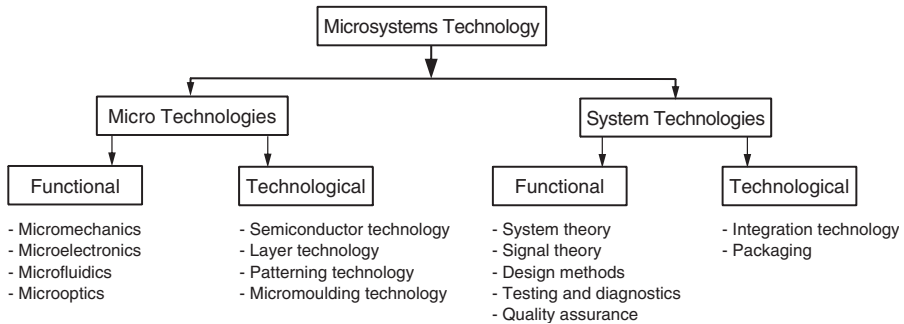


Figure 1.4 Microsystem technology

the size lies in the range between micrometers and nanometers (Figure 1.3). Such small structural sizes can be achieved by directly using or adapting manufacturing methods of semiconductor technology as well as through specifically developed manufacturing processes that are close to microelectronics (Figure 1.4).

- Recently, nanotechnology has started enjoying massive public attention. The prefix ‘nano’ is used there in two respects. On the one hand, nanotechnology can be applied to downscaling typical sizes, such as the thickness of function layers, from the micrometer down to the nanometer range. Today, typical gate thickness in microelectronic CMOS transistors is only a few dozen nanometers. Here, the term nanotechnology (nanoelectronics, nanoelectronic components) is used for an extremely diminished microtechnology where the known description and design procedures can be applied. On the other hand, the term nanotechnology is used for procedures and components which are only found at a certain miniaturized level. Examples are quantum effects (e.g. quantum dots) as well as tunnel effect devices or single-electron components. This textbook will not address such components.
- Microsystems consist of several components which, in turn, consist of function and form elements (Figure 1.5). The components have specific functions, e.g. sensor, actuator,

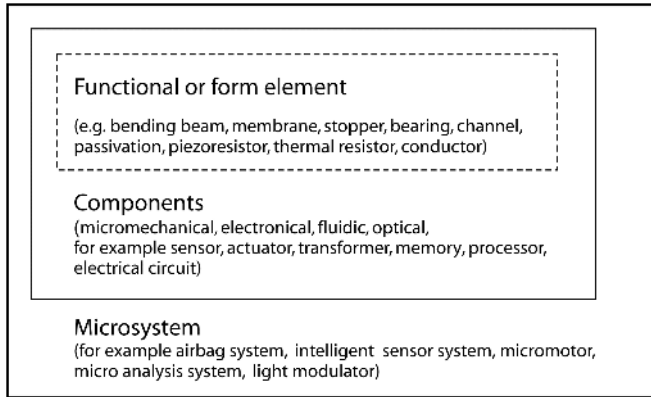


Figure 1.5 Terminological hierarchy in microsystem technology

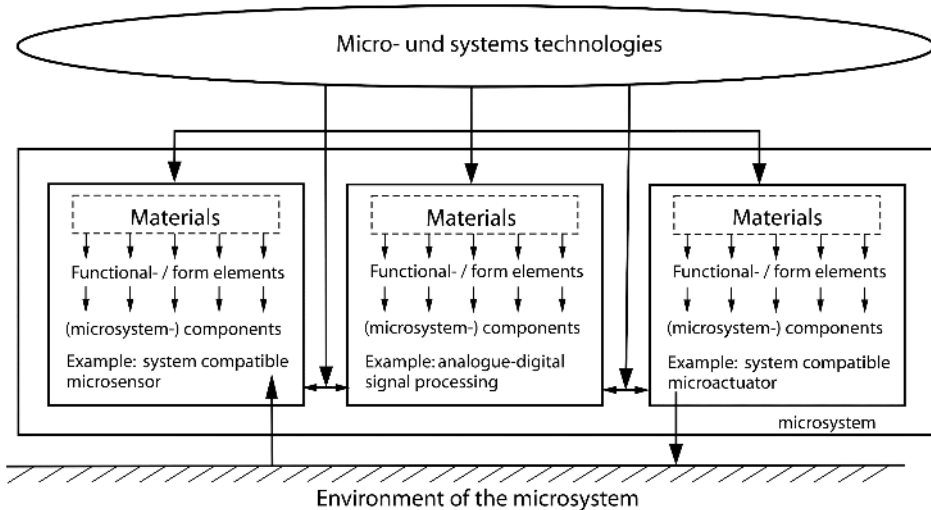


Figure 1.6 Structure and integration of microsystems

transformation, memory or signal processing functions and they can be constructively autonomous entities (e.g. an integrated circuit). Microsystems include both nonelectric and (micro-)electronic as well as electrical components. The system character is due to the fact that the system can only fulfil the total function if the components interact as a complex miniaturized unity.

Figure 1.6 shows the typical design of microsystems. Sensors and actuators as well as signal processing components that are suitable for system integration are – via appropriate interfaces – integrated with each other but also with the microsystem’s environment, e.g. with a technical process that has to be controlled. The individual components consist each of a number of function and form elements that can be produced using corresponding materials and applying micro- and system technology. Microsystem technology is also used for the functional integration of the system components.

In summary, we can define ‘microsystem’ as follows:
A microsystem is an integrated, miniaturized system that

- comprises electrical, mechanical and even other (e.g. optical, fluidic, chemical, biological) components;
- is produced by means of semiconductor and microtechnological manufacturing processes;
- contains sensor, actuator and signal functions;
- comprises function elements and components in the range of micro- and nanometers and has itself dimensions in the range of micro- or millimeters.

This definition does not strictly distinguish between micro- and nanosystems. As microelectronics already uses ultrathin layers of only a few nanometers it has crossed the line to nanotechnology. Piezoresistive resistors are standard function elements in microsystem technology and they act as conduction areas for a two-dimensional electron gas if they are less than 10 nm thick.² The resulting quantum effects lead to a substantial increase in the piezoresistive coefficients. Microsystems usually contain electrical and mechanical components as a minimum.

Thus, sensors have function elements for detecting non-electrical values (e.g. mechanical deformation values such as cantilevers or bending plates which are deformed by the effect of the measurand force or pressure), transformer elements for transforming the measurand into electrical values (e.g. piezoresistive resistors in the cantilever elements) as well as components for processing electrical signals. Vice versa, the same applies to electromechanical drives. Electrical functions and their corresponding microsystem components are used for signal extraction and processing as well as for power supply. At the same time, microsystems have – as a minimum – mechanical support functions, often even further reaching mechanical functionalities.

Coinciding with its purpose, a microsystem can also have other function elements in addition to the electrical and mechanical ones. The smallness of a microsystem’s function components is often a prerequisite for applying a certain function principle. On the other hand, however, miniaturization makes a coupling to technical systems in our ‘macroworld’ more difficult. Therefore, complete microsystems often have dimensions in the range of millimeters which clearly facilitates their integration into other systems. Here the transition from the micro- to macroworld already takes place in the packaging of microsystems. However, even here the term microsystem is commonly used.

1.2 MICROELECTRONICS AND MICROSYSTEM TECHNOLOGY

The development of microsystem technology is the immediate result of microelectronics which shows two major drawbacks:

²Ivanov, T. (2004) *Piezoresistive Cantilever with an Integrated Bimorph Actuator*. PhD Thesis. University of Kassel.

1. Microelectronics is limited to electronic devices and the integration of electronic functions. Usually, it is not possible to process non-electrical values. Building complex systems that are able to use sensors to read signals from the system environment and to affect the environment via actuators requires a combination of microelectronic components and classical components produced by precision mechanics. This reduces the miniaturizing potential and the level of integration that can be reached. Thus, reliability decreases.
2. Basically, the manufacturing process of semiconductor technology can only be used to produce two-dimensional but not three-dimensional structures. However, a number of functions – especially nonelectrical ones – require three-dimensional function components and their three-dimensional integration.

There are several reasons for the close connection of the development of microsystem technology with microelectronics:

- Within microtechnologies such as micromechanics, microfluidics, microoptics etc., microelectronics has an outstanding position. Given the current state of the art, microsystems without microelectronic components for processing analogous or digital signals appear not to be meaningful.
- Only semiconductor and thin film technology provides manufacturing processes that are able to produce structures in the range of micro- and nanometers. And there are additional advantages of microelectronic manufacturing processes that can be used: the parallel processing of identical elements or components within one and the same manufacturing process as well as the use of completely new physical-chemical procedures which differ substantially from classical manufacturing technologies.
- Often, microsystem technology uses materials that are used in microelectronics. Both microsystem technology and microelectronics are dominated by silicon which has excellent characteristics in comparison with compound semiconductors, for instance. On the one hand, this is due to the fact that electronic components are very important in microsystems and therefore silicon particularly is qualified for integration technologies. On the other hand, silicon can be produced with the highest chemical purity and crystal perfection. And a large number of technological procedures and sensoric as well as actuating effects rely in particular on these crystal features.

Table 1.2 compares typical characteristics of microelectronics and microsystem technology. The given characteristics show that microsystem technology will even in the future mainly use microelectronic technologies. Large production numbers and a high standardization of components in microelectronics are due to the programming options of microprocessors and microcomputers as well as memory circuits. Therefore, silicon-based technology was able to attract development prospects that by far exceed those of microsystem technology. Due to the diversity and heterogeneity of microsystem technology, it will not be possible to find similarly standardized applications with similarly high production numbers. The only option here is to use highly developed fabrication methods of semiconductor technology. Original technological developments, such as the LIGA technology, are rather the exception. Currently, the following developments can be discerned regarding the use of microelectronic manufacturing methods:

Table 1.2 Comparison of typical characteristics of microelectronics and microsystem technology

Criterion	Microelectronics	Microsystem technology
Components	standardized (e.g. memories, processors)	heterogeneous
Production numbers	$10^5 \dots 10^8$	$10^2 \dots 10^6$
Applications	electrical	mechanical, electrical, fluidic, optical, ...
Structural dimension	two-dimensional	three-dimensional
Design	automated	heterogeneous with limited design support

- transfer of two-dimensional structuring processes on to three-dimensional applications (e.g. surface and near-surface micromachining, see Chapter 4);
- development of modified system integration technologies (e.g. packaging, see Chapter 5);
- further development und adaptation of microelectronic design methods to complex heterogeneous systems, which are characteristic of microsystem technology (see Chapter 8).

1.3 AREAS OF APPLICATION AND TRENDS OF DEVELOPMENT

Initially, the development of microsystem technology was related to the study (1953–58) and commercialization (1958–72) of piezoresistive sensors [GERLACH05]. Since then, the range has become dramatically wider [KOVACS98]. In the beginning, the focus was on the advantages of miniaturization for new automotive applications (measuring manifold pressure of combustion engines in order to reduce emissions) and invasive biomedical sensors, for instance. Today, new areas of application are of major interest, allowing for large production numbers, low cost per unit and high reliability.

Currently, the following are important examples of the application of microsystems:

- **Automation technology:** Modern cars contain a large number of new systems for improved driving safety and comfort. Microsystem technologies can be used to produce large volumes with low system cost and high reliability. Examples are acceleration sensors for ABS and airbag applications, yaw rate sensors for driving stability and airflow sensors for controlling air conditioning. More than half of all microsystem applications is used by the automotive industry.
- **Medical technology:** Microsystems with dimensions in the range of micro and millimeters can be widely used for invasive applications. Important examples are catheters for measuring heart pressure, probes for minimal invasive diagnostics and therapy as well as dosing systems.

- Environmental technology, gene technology and biotechnology: Microanalysis and micro-dosing systems can be used for the chemical and biotechnological analysis of gases and fluids. Microreactors can be used for chemical processes involving very small volumes and other uncommon conditions.
- Microfluid systems: Ink jet nozzles can be produced at low cost using miniaturized integration of electrical, mechanical and fluidic functions.
- Nanotechnology: The production, manipulation and characterization of nanostructures require tools for ultra-precise movement and positioning. Systems that are based on scanning tunneling and atomic force effects often use miniaturized cantilevers with tips in the range of nanometers. Microsystem technology can effectively produce such tools.

Considering the further development of microsystem technology, the following trends can be discerned:

- Microsystem solutions require mainly applications with large production numbers.
- The manufacturing of microsystems increasingly uses commercial semiconductor processes. The development of special technologies is only possible when large production numbers justify the costs or when there are no alternatives to microsystems and therefore a high per-unit price can be realized. This is the case of minimal-invasive medical applications, for instance.
- Reliability and lifetime of microsystems as well as long-term stability and accuracy become ever more important, particularly regarding industrial applications of chemical and biological sensors and analysis systems.
- The economic rather than the technological framework decides which integration technologies are used for producing microsystems. Whereas in the past the monolithic integration was a main goal, today almost exclusively hybrid integration is used for smaller production numbers. Nevertheless, there are substantial efforts to further develop monolithic integration methods, in particular those that try to integrate microtechnologies into commercial semiconductor manufacturing processes (e.g. CMOS processes). The three-dimensional design and integration of alternative methods of microsystem technology then takes place mainly as a back-end process following the conventional microelectronic manufacturing process.
- Microsystems are based mainly on microelectronic materials and methods. Therefore, a main issue of the development of microsystems is the design process. Currently, there is a substantial need for developing appropriate design tools for modeling and simulating complex and heterogeneous systems (see Chapter 8).

1.4 EXAMPLE: YAW RATE SENSOR

In the following, we want to use an example to present a complex microsystem. We will show how a microsystem is constructed with various components and function elements.

We also want to show that the characteristics of the material, manufacturing technology and design are closely interconnected.

1.4.1 Structure and Function

The rotating speed Ω (yaw rate) is an important parameter of bodies moving in space. Yaw rate sensors are therefore very important for the driving stability of cars. Figure 1.7 and Figure 1.9 show a yaw rate sensor that is based on the CORIOLIS principle.

The sensor consists of a silicon chip. Methods of bulk micromachining (see Section 4.6) are used to etch away two masses suspended on springs. In the magnetic constant field B_z , an alternating current I_y induces through conducting lines sinusoidal Lorentz forces F_x on the cantilevers. These forces cause masses m to oscillate harmoniously with speed v_x in direction x (compare the effect chain in Figure 1.8). When the two masses oscillate in opposite direction, the sensor chip remains, in total, motionless and can be translatory considered to be fixed. Both cantilevers and masses consist of single crystalline silicon (compare Section 3.2) and show therefore a long-time stable, ideal elastic behavior. If a yaw rate Ω_z operates vertically to the direction of the oscillation, CORIOLIS force F_x results in direction y .

In this example, a capacitive accelerometer is used to evaluate this force. It has the design of an interdigital finger structure with fingers that are fixed to the masses and other fingers between those fingers. The movable fingers are attached to a middle link that is suspended flexibly over the cantilevers. CORIOLIS force F_y can thus displace mass m_{ACC} of the accelerometer by a distance s_y , which in turn changes capacity ΔC between movable and fixed fingers in relation to their distance from each other. The capacity change of the accelerometer can be transformed into an electronic signal, e.g. voltage change $\Delta V(\Omega)$ or frequency change $\Delta f(\Omega)$.

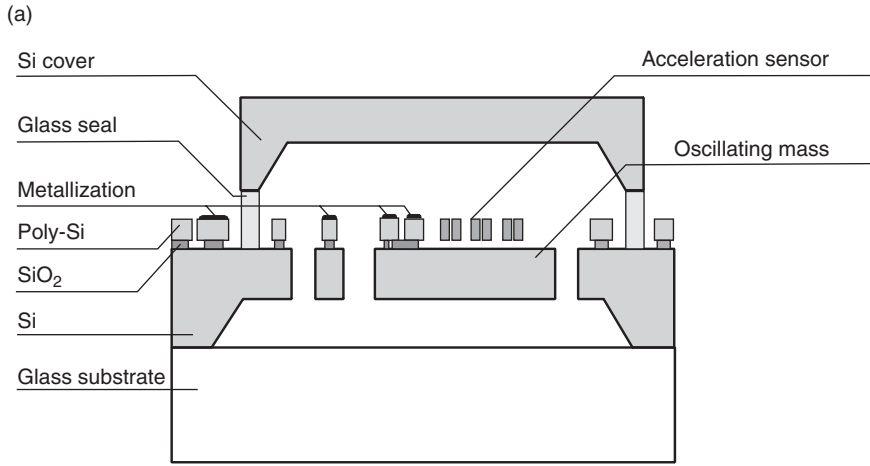
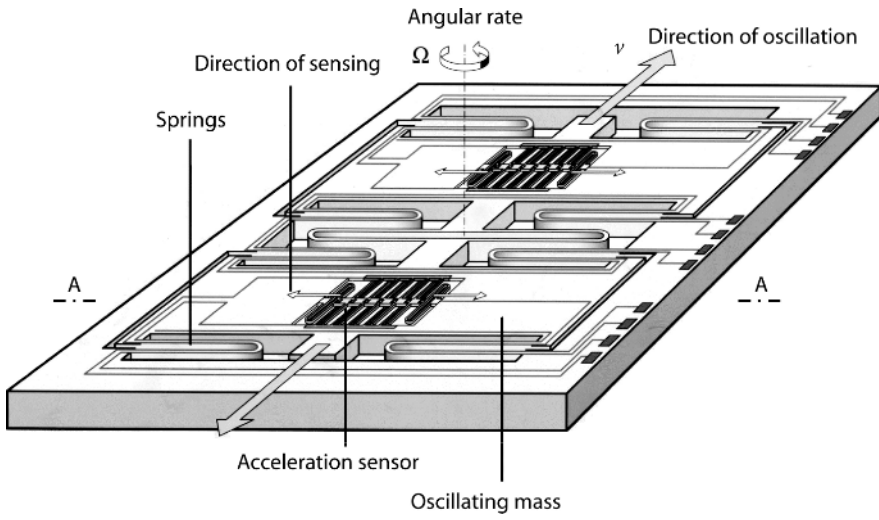
Methods of surface micromachining (see Section 4.11) are used for producing the accelerometer on a silicon mass m . Thin films with a thickness in the range of a few micrometers are separated and selectively structured. The characteristics of these layers determines the behavior of the accelerometer.

Methods of packaging (see Chapter 5) are used to integrate the sensor chip into a casing and thus to guarantee a safe and reliable operation of the sensor. The casing consists of a glass substrate with a coefficient of linear thermal extension adapted to the silicon as well as of an accordingly shaped silicon cover.

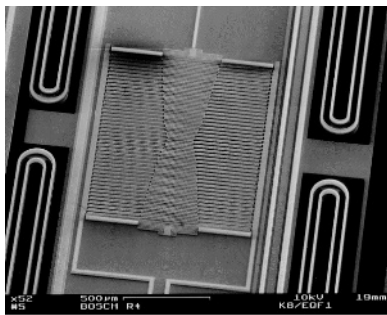
1.4.2 Function Components and Elements

The yaw rate sensor consists of two components (Figure 1.8):

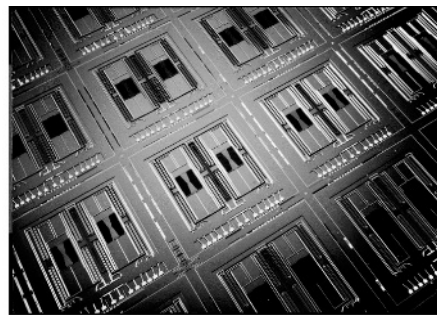
- Electrically oscillated mass m (electromechanical actuator). Mass m and the four cantilevers n_x are the function elements and form an oscillatory mechanical resonant system.
- Yaw-rate related interdigital capacitor (accelerometer). This mechanical-electric sensor structure consists of oscillating mass m with a firmly attached finger structure, an



(b)



(c)



(d)

Figure 1.7 Yaw rate sensor: (a) 3D image; (b) cross section A-A; (c) microscope image; (d) several sensors on-wafer. Reproduced by permission of Robert Bosch GmbH, Germany

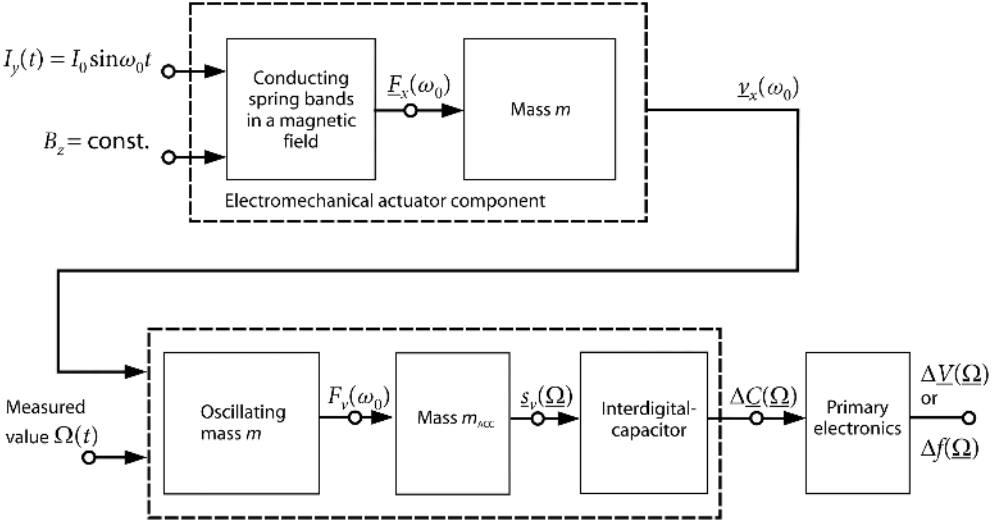


Figure 1.8 Effect chain of the yaw rate sensor in Figure 1.7

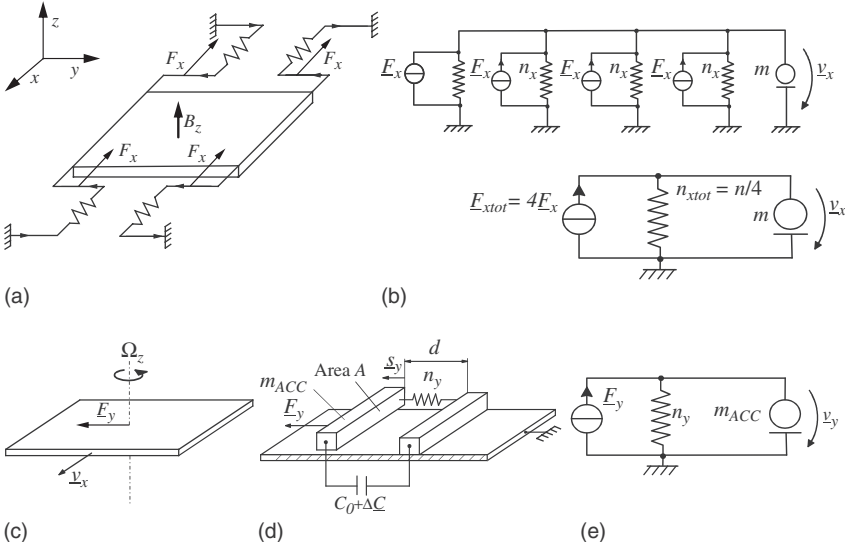


Figure 1.9 Details of the yaw rate sensor in Figure 1.7: (a) oscillating mass m with current I on the cantilevers; (b) mechanical block diagram of the oscillating mass affected by LORENTZ force F_x ; (c) CORIOLIS force F_y as a result of yaw rate Ω ; (d) detailed presentation of the capacitive finger structure of the accelerometer on oscillating mass m ; (e) mechanical scheme of the interdigital transformer in (d)

elastically suspended (compliance n_y) movable finger structure (mass m_{ACC}) and the capacitor electrodes formed by those.

The underlying physical principles can be used to describe the effect of function elements, function components and the entire microsystem. In the following, we will show this for the individual function elements.

Figure 1.9a schematically represents the function elements of the electro-mechanical actuator that induces sinusoidal oscillation motions of the accelerometer. Mass m is suspended by four cantilevers n_x . They form a parallel-motion joint that restricts translatory displacement in direction x . There are conducting lines on the cantilevers that carry an alternating current $I_y(t) = I_0 \cdot \sin \omega_0 t$, where ω_0 is the angular frequency of the excitation current.

If the magnetic field operates in direction z , on each of the cantilevers with an orientation in direction y and a length ℓ_y the following LORENTZ force will result according to the law of BIOT-SAVART

$$\vec{F}_x = I \ell_y (\vec{e}_y \times \vec{B}) \quad \text{or} \quad (1.1)$$

$$F_x(t) = I(t) \cdot \ell_y \cdot B_z \quad (1.2)$$

in positive or negative direction x , respectively.

Force F_x periodically deforms the corresponding cantilever part n_x and contributes to displacing mass m . If the current flows in the correct direction through all four cantilever elements, the partial forces add up as is shown in the mechanical scheme in Figure 1.9b. The resulting total force F_{xtot} amounts to four times the individual forces:

$$\underline{F}_{xtot} = 4\underline{F}_x. \quad (1.3)$$

Total compliance n_{xtot} amounts to only one-fourth of the individual compliances n_x :

$$n_{xtot} = n_x \| n_x \| n_x \| n_x = n_x / 4. \quad (1.4)$$

Thus, the displacement of mass m is

$$\begin{aligned} \underline{v}_x &= \underline{F}_{xtot} \cdot \left(j\omega_0 n_{xtot} \parallel \frac{1}{j\omega_0 m} \right) = \underline{F}_{xtot} \cdot \frac{j\omega_0 n_{xtot} \cdot \frac{1}{j\omega_0 m}}{j\omega_0 n_{xtot} + \frac{1}{j\omega_0 m}} \\ &= \underline{F}_{xtot} \cdot j\omega_0 n_{xtot} \frac{1}{1 - \omega_0^2 m n_{xtot}} \end{aligned} \quad (1.5)$$

or applying Equation (1.2)

$$\underline{v}_x = j\omega_0 n_{xtot} \ell_y B_z \underline{I} \frac{1}{1 - \omega_0^2 m n_{xtot}}. \quad (1.6)$$

The imaginary unit j describes the phase displacement between current $I(t)$ and oscillation rate $v_x(t)$ of the mass. The last term of Equation (1.6) derives from the fact that

m_x and n_{xtot} form a resonant system. For $\omega_0^2 \cdot mn_{xtot} = 1$, \underline{v}_x would be infinite. In practice, such systems are operated in resonance as they require only little power input to reach large oscillation amplitudes. The displacement, however, cannot become infinitely large due to damping effects, which were neglected before. Assuming that in Figure 1.9b there is a friction $r = \underline{F}_r / \underline{v}_x$ parallel to n_{xtot} and m , the term $j\omega_0 m$ in Equation (1.5) would have to be replaced by $(j\omega_0 m + r)$. Including resonance quality $Q = 1 / \omega_0 nr$, Equations (1.5) and (1.6) result in

$$\underline{v}_x = j\omega_0 n_{xtot} \ell_y B_z \underline{I} \frac{1}{1 - \omega_0^2 mn_{xtot} + j \frac{1}{Q}} \quad (1.7)$$

or for $\omega_0^2 = 1 / mn_{xtot}$

$$\underline{v}_x = \omega_0 n_{xtot} \ell_y B_z \underline{I} \cdot Q. \quad (1.8)$$

Quality Q typically has a value of approximately 10 in air and of $10^4 \dots 10^6$ in vacuum.

Due to yaw rate $\Omega(t)$, CORIOLIS force

$$\vec{F}_y = 2m(\vec{v}_x \times \vec{\Omega}_z). \quad (1.9)$$

operates on the oscillating mass m .

For an arrangement according to Figure 1.9c there results for the scalar components

$$\underline{F}_y = 2m \underline{v}_x \cdot \underline{\Omega}_z = \omega_0 n_{xtot} \ell_y B_z Q \underline{I} \cdot \underline{\Omega}_z. \quad (1.10)$$

The interdigital structure of the accelerometer located on mass m can be represented according to Figure 1.9d. The result is an oscillatory system consisting of mass m_{ACC} of the movable fingers and total compliance n_y of the finger suspension. Analogous to the system in Figure 1.9a, there results the mechanical scheme in Figure 1.9e. Displacement \underline{s}_y of the movable finger electrodes is thus

$$\underline{s}_y = \frac{\underline{v}_y}{j\omega} = \underline{F}_y n_y \cdot \frac{1}{1 - \omega^2 m_{ACC} n_y}. \quad (1.11)$$

Rotating speed Ω corresponds here to the yaw rate frequency which, in practical applications, can be replaced by complex angular frequencies as the measurand $\Omega(t) = \underline{\Omega}_z(t)$ can have any time function.

Including Equations (1.10) and (1.11), the yaw-rate related displacement of the left movable finger in Figure 1.9d results in

$$\frac{\Delta C}{C_0} \approx -\frac{\underline{s}_y}{d} = \omega_0 Q n_{xtot} n_y \ell_y \frac{1}{d} B_z \underline{I}(\omega_0) \frac{1}{1 - \omega^2 m_{ACC} \cdot n_y} \cdot \underline{\Omega}(\omega). \quad (1.12)$$

The following conclusions can be drawn from Equation (1.12):

- Large capacity changes can be achieved by using elastically suspended masses m (high compliance n_x , large ℓ_y).

- A high quality factor Q can be reached in vacuum. This requires integration methods for the system construction that correspond to Figure 1.7b and can be carried out in vacuum in order to avoid subsequent evacuation.
- Distance d between the finger elements of the interdigital capacitor should lie in the range of micrometer. It has to substantially exceed maximum displacement s_y , though.
- B_z is limited due to the magnetic flux density of typical hard magnets and lies in the range below 1 T.
- Feeding current I of the electro-mechanical actuator is limited by resistance losses in the conducting lines and by the small feeding voltages that are frequently used in microsystem technology and microelectronics.

EXERCISES

- 1.1 Explain the function principles of the microsystems in Figure 1.2.
- 1.2 Characterize function elements and components of the following microsystems:
 - (a) piezoresistive pressure sensor (Section 7.2.5, Figure 7.23);
 - (b) micropump (Section 6.2.4, Figure 6.13);
 - (c) bolometer array.
- 1.3 Search the Internet for examples of microsystems in the areas of automotive sensors (pressure sensors, crash sensors, air flow sensors, yaw rate sensors), medical catheter sensors, ink-jet technology and micro-analysis systems.

REFERENCES

- [GERLACH05] Gerlach, G., Werthschützky, R. (2005) 50 Jahre Entdeckung des piezoresistiven Effekts – Geschichte und Entwicklung piezoresistiver Sensoren. *Technisches Messen* **72** (2005) 2, pp. 53–76, and 50 years of piezoresistive sensors – History and state of the art in piezoresistive sensor technology. In: Sensor 2005, 12th *International Conference, Nürnberg, 10–12 May 2005. Proceedings*, vol. I. AMA 2005, pp. 11–16.
- [KOVACS98] Kovacs, G.T.A. (1998) *Micromachined Transducers Sourcebook*. Boston: WCB/McGraw-Hill.

