MICRO ELECTRO-MECHANICAL SYSTEMS – MEMS

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Summary

MEMS have characteristic dimensions in the micrometer range. The integration of nano-scale effects and materials is ante portas. MEMS technologies have become a mature industrial platform with a steadily growing number of killer applications in the automotive, consumer, industrial and medical fields. MEMS is not a homogeneous industrial branch but rather an approach to create microscale devices for all possible applications using microfabrication technologies including non-standard packaging and test methods, and exploiting an ever growing repertoire of MEMS-building blocks. Beside fabrication technologies, transducers which convert signals from one physical domain to another are key tools for creating links between the outer world and the information processing systems as well as between the different physical, chemical or biological effects that are combined in a given MEMS. A broad spectrum of transducers like piezoresistive, piezoelectric and capacitive stress/deflection-to-voltage converters, thermal sensors and actuators, magnetic transducers, optical sensors and actuators, flow sensors and fluidic actuators have been created by the MEMS community using new materials and technologies. It is continuously expanding and more and more also includes nano-technologies.

Many operating principles for creating ready-for-application micro-sensors and actuators have been newly developed or adapted to the MEMS environment. Pressure sensors, accelerometers, gyroscopes, fluidic MEMS and BioMEMS, opto-electromechanical systems for light projectors and optical communication as well as RF-MEMS exploit a great variety of different functional principles and, hence, system solutions. The tight interdependence of a given application target and the corresponding MEMS technologies requires a strong interaction of application experts and MEMS specialists, which in the end is the basis for a successful MEMS product.

1. Introduction

The chapter gives an overview on the nature of MEMS, their main application areas, on the most important transducers and MEMS technologies as well as on some operating principles used to design various MEMS.

The term ‘Microelectromechanical systems’ has been created in 1987 during some subsequent workshops on microdynamics in order to differentiate from electronic integrated circuits (IC) the myriad of new product ideas and prototypes emerging within the microelectronics environment. The new MEMS-products have characteristic dimensions between sub-micrometers and hundreds of micrometers and typical sizes between parts of mm² and hundreds of mm³. They are fabricated by microelectronic technologies and their extensions – often summarized under the concept of ‘micromachining’, a term which came up in 1982. In contrast to microelectronic
devices, MEMS integrate non-electronic effects based on movable parts, mechanical resonators, tunneling tips, electrolytic and other fluids, active chemical and biological reactions, optical beam forming and redirection and others. Accordingly, the repertoire of basic MEMS-elements includes proof masses, springs, diaphragms, capacitances with movable electrodes, beams, mechanical RF-resonators and filters, piezoresistive and piezoelectric transducers, mechanical switches, gears, nozzles, valves, pumps, mirrors, micro lenses, beam splitters, hotplates, thermal actuators, Hall elements – to name just a few. Today there is a tendency to sub-summarize all microsystems with multi-domain or non-electronic functionality under the MEMS umbrella. A common feature is that the multi-domain character of MEMS implies signal transformations between domains. Therefore, micro-transducers play a fundamental role in designing MEMS.

In general, MEMS elements are not simply scaled-down macroscopic devices ([23]). The micro-world is dominated by completely different relationships between the various physical effects. The basic reason is that a geometric down-scaling of the characteristic dimensions changes the ratio between volume and surface. The volume reduces faster than the surface leading to an increased weight of surface effects like adhesion, stiction, mechanical noise, structural and surface-caused damping, surface-state-dominated instabilities etc. For instance, inertial forces that are proportional to the volume become comparable to damping forces which are determined predominantly by the interaction of the surface with a gaseous environment. The characteristic mass movements in MEMS cover a huge velocity range from sub-micrometer per second up to many meters per second. Therefore, the impact of viscous forces, friction and fatigue may be dictated by completely different mechanisms. Many of such micro-scale effects are very complex and are subject to intense research trying to understand the performance limits of different MEMS elements.

MEMS technologies are basically based on batch fabrication. As in the case of microelectronics, the wafer remains the basic carrier of the MEMS component dies. Thousands of dies can be fabricated in parallel, making this approach attractive also for small MEMS companies. Silicon substrates appear as basic material. However, glass, quartz, SiC, GaAs, Ge and other materials are also used. Further, a broad spectrum of new materials including ceramics and polymers has been adapted for forming MEMS elements. Moreover, the fabrication sequence of MEMS often consists of additional processes such as the so called Zero-level-packaging (see Section 4.1). Most of the active MEMS elements are electrically excited or sensed. The corresponding electronic signal-conditioning and possible trim and test support may be performed on-chip or off-chip. In the first case one speaks of monolithic integration, which puts additional challenges on technology integration and is technically and economically not always favorable.

The overwhelming majority of MEMS products are sensors and actuators. They provide control systems with 'eyes, ears and noses' to acquire information on the status of the object to be controlled. They can directly perform some specific actions like fluid transport in microsystems (e.g. droplet generation in ink-jet cartridges) or initiate actions in the macro world. However, many new functions emerge. Among them are micro-energy sources such as micro fuel cells, energy harvesting based on the transformation of kinetic energy (e.g. vibrations) and of solar and thermal energy into
charge, and remote energy supply. They open the way to building supply-independent
sensor networks which are especially needed for environmental monitoring and
protection. A prerequisite is often the integration of wireless communication, as it is
state-of-the art, for instance, in tire pressure monitoring sensors. The broad range of
functional principles, governing micro-scale effects and technologies makes the MEMS
area a multidisciplinary field where engineering disciplines and basic research are
tightly interwoven. Since the MEMS product is usually only a component within a
complex application that requires an often not less complicated research and/or design
work, the link between MEMS and its applications must be covered by a broad
penetration of MEMS knowledge into the different application areas. The integration of
MEMS courses into the basic engineering education is one way to support the
propagation of the MEMS paradigm into the development of new products and systems
in nearly all areas of human endeavor.

2. MEMS Applications and Market

A commercial MEMS-device is a packaged, calibrated, and tested product, which has to
satisfy very different application conditions with respect to temperature range, shock
robustness, life-time, reliability etc. Orders of magnitude may separate the complexity
and the price of MEMS for different applications even if the underlying principles are
identical. The extreme diverseness of application requirements entails very fragmented
markets which have predominantly low volume and only few large to truly high volume
applications.

The early stage of MEMS is characterized by broad research, technology development
and creation of MEMS prototypes in order to find out their cost and performance limits.
High-volume production and mass applications have been the exception. Among them
are the well known first diaphragm-based, piezoresistive MEMS pressure sensor
successfully marketed around 1974 by National Semiconductor and the MEMS-based
bubble jet print-head developed around 1979 by Canon and commercialized by Hewlett-
Packard in 1984 (see [40]). Within the last decade the MEMS market is transforming
more and more into a high volume market with steadily expanding size, and, crucially,
with growing number of different application classes. MEMS have become an
established industry with impressive growth and an increasing number of well defined
applications ([33]) which feature typical Compound Annual Growth Rates (CAGR)
between 5% and 20%.

In the 1990s three to five years were needed to develop new MEMS designs and five to
eight years were required from prototypes to volume production. Texas Instruments
started the research for the Digital Light Processing (DLP) and digital micro-mirror
device (DMD) in 1976 and only about 20 years later commercialized it. It is now the
heart of beamers and microdisplays. Now – within the established MEMS environment
– the typical overall time from design start to volume production has decreased by a
factor of two to three and is shrinking further. According [13] 150 companies
manufactured in 2009 about 98 % of the commercial MEMS devices – altogether
around $ 6 Bill. A doubling is expected until 2015. More than 90 R & D industrial
facilities, which are able to develop prototypes and to perform small volume production,
and a countless number of university laboratories, round off the picture of today’s MEMS community.

The largest MEMS producer in 2009 was Hewlett Packard with its ink-jet print heads; the second place was occupied by Texas instruments with its DMD. The largest MEMS-sensor producer – the company Bosch – followed on third place.

Most likely, in the next years accelerometers will occupy the first place and displace the long-time leading ink-jets. For the next years the expected CAGR for the whole MEMS market is around 10 - 12 % – about 25 % higher than the corresponding value for the semiconductor market ([25]), which in 2009 has been approximately 50 times larger than the MEMS market. However, the importance of MEMS is primarily not determined by their market share, but by the new applications which become possible in combination with other macro- and micro-technologies.

It should be noted that the MEMS market sometimes is understood as the market of MEMS systems and not of MEMS devices. Here a MEMS system represents the complete module ready for inserting into the next higher-level system. Correspondingly the price difference between both may be one to two orders of magnitude.

2.1. Mechanical MEMS

Pressure sensors belong to the oldest MEMS and are used under harsh conditions in cars, for instance, controlling the air-fuel ratio for the engine and the hydrocarbon emission, or monitoring the tire pressure. They are used in medicine for invasive and non-invasive blood pressure measurement, for the control of infusion pumps, micro-pumps, etc. They can be integrated in sports watches, but also in cell-phone to support level-detection in the upcoming in door navigation systems. Their market share in 2010 was about 15 % of the overall MEMS device market.

MEMS microphones for portable electronics and especially for cell-phones quickly gained market shares. Due to their solderability they offer substantial cost advantages against the excellent electret microphones.

Autofocus and zoom actuators for digital cameras are another high volume application of mechanical MEMS. For instance, capacitive comb actuators are used to move lenses within the photoobjective. MEMS with movable nanometer-sharp tips are used for material surface investigation down to the atomic scale as, e.g., in the atomic force microscopes (AFM).

The Millipede from IBM Research, Zurich ([19]), is another example of prototyping possible fundamental new applications – here for ultradense information storage in the range of Terabit/inch² on very thin polymer films by using an array of thermomechanical scanning probes. Mechanical MEMS actuators for driving cutting tools in microsurgical applications have become indispensable tools in medicine, especially for neurosurgeons. Microengines with small gears at rotational speeds greater than some 100,000 rpm have been prototyped. Possible applications include driving the wheels of microcombination locks or pop-up micro-mirrors.
2.2. Inertial Sensors

Basically, inertial sensors belong to the mechanical sensors. They include accelerometers for cars, for instance, for airbag release, for tilt measurement and antiskid systems. Accelerometers are integrated in laptops in order to detect a possible free-fall and to bring the disc-head into a safe position before crash. In smartphones and iPad displays they perform portrait-landscape detection depending on the vertical or horizontal position of the display.

In the medical area activity control of, e.g., patients with pacemakers or of sportsman are well-known applications. Gyroscopes are the second type of inertial sensors and used, for instance, in cars for electronic stabilization systems (ESP), for roll-over detection and antiskid systems. In digital cameras they support image stabilization. The combination of accelerometers and gyroscopes allows to aid navigation not only in cars (dead reckoning) but also within buildings (in door navigation), where GPS-navigation suffers from bad reception.

Three axes (3D) accelerometers and 3D gyroscopes are combined with 3D magnetometers in order to have an external, stable reference angle given by the local magnetic field. Adding a pressure sensor level detection in buildings becomes possible. Such systems which consist of a set of MEMS chips are presently in wide introduction in smartphones and aid the orientation within fair halls and other building complexes. Sensor fusion for such complex applications is a challenge and normally performed by programmable sensor fusion IC’s.

Game controllers or, more generally, human-computer interfaces are another booming application of inertial sensors. The motion of the platform is analyzed and initiates different on-line commands. Beside motion pods for medical applications such systems also find growing acceptance in fitness and sport. Overall, the inertial sensor market in 2010 was the largest segment with a share of about 30 %.

2.3. Microfluidics

In 2010 microfluidic devices have had a share of about 28 %, of which 25 % stem from the ink-jet device mentioned above. Microfluidic devices transport and store fluids. The quantities are in the order of nanoliter or less. They inject, separate, and merge continuous liquids or droplets and are especially promising for drug dispensing and the miniaturization of medical, biotechnological and chemical analysis (Lab-on-a chip, DNA-chips). Fuel cells for electric energy generation are under development. The applications of microfluidic devices are countless, however, apart from the ink-jet, they are mainly in the early stage of broad industrialization.

2.4. Micro-Opto-Electromechanical Systems (MOEMS)

The DMD chip from Texas Instruments for displays based on digital light processing is the most popular and high volume representative of MOEMS. An alternative that is gaining market share is the interferometric modulator display (IMOD) from Qualcomm based on interferometric color selection.
Optical laser scanners based on oscillating micro-mirrors are used, for instance, for fast bar code reading or for obstacle detection. They represent the class of MEMS-based imaging systems with active illumination. Micro-mirror-based optical switches for routing optical signals between fibers in cross connects represent key elements for improved performance of optical networks. Attenuators, tunable optical filters, beam splitters, analogue and digital light modulators, microlenses etc. are other basic devices, used in a great variety of applications. The optical switch segment was over-hyped before the crash of some network companies in 2001-2002 by unrealistic expectations, however since then has taken a solid development.

2.5. RF MEMS

RF MEMS are mechanical resonators, switches, varactors, tunable mechanical filters etc. aimed at operating in wireless communication systems in the upper MHz and GHz-range. The development is driven by the high-performance requirements of test equipment, radar and multi-band cell-phones. Mechanical resonators have begun to substitute expensive and bulky quartz clocks – a multi billion market. Their advantage is lower power consumption and the possibility to be cointegrated with IC’s. The performance of high-temperature compensated quartz resonators is achievable.

2.6. Magnetic MEMS

Hall sensors are fabricated for long using standard microelectronic technologies. Magnetic sensors based on the Anisotropic Magnetoresistive (AMR) or the Giant MagnetoResistive effect (GMR) have been developed also independently on MEMS efforts. They are used mainly for angular and position measurement within industry, for current sensing and for the measurement of external magnetic fields. MEMS technologies have extended the possibilities of magnetic microsystems especially with respect to performance improvement. In the last years magnetic sensors have found applications in cell phones where they function like a compass detecting the orientation of the Earth’s magnetic field (30 to 60 \( \mu \) Tesla).

The drawback of many magnetic MEMS is the need of an external magnet which occupies size and weight. Hard-magnetic materials deposited on-chip are used to produce internal magnetic fields which are necessary, for instance, for magnetic write-read heads of magnetic discs.

2.7. Other MEMS

There exist many MEMS which do not fit unambiguously into the above classes. For instance, non-fluidic bio and chemical MEMS based on thermomechanical, weight-changing absorption or chemical reactions are using thermo-chemical-mechanical effects. Thermal sensors and actuators like heat pumps exploit a combination of various thermoelectrical and thermomechanical effects. Often the corresponding devices act as transducers of higher-level MEMS devices. BioMEMS cover a broad spectrum of domain specific MEMS and their combinations for diagnosis, drug delivery, neural prosthetics, tissue engineering and minimal invasive surgery ([16]). They integrate, for
instance, on-chip opto-electrical or acoustic-electrical transducers with connections to neurons, like in the case of artificial retinas or hearing aids.

3. Transducers

This section gives a short introduction to the main transducer principles used in MEMS. MEMS transducers form the links between signals of different energy domains. Most MEMS consist of several transducers. For instance, an acceleration sensor includes a mechanical transducer which transforms the inertial force (mechanical energy) via moving masses and suspensions into displacements or stress and strain in the elastic members (elastic energy). The subsequent electrical transducer converts the latter into electrical output signals.

Silicon (Si) with its outstanding mechanical properties (see, e.g., [21],[23] and [46]) plays a key role for building transducers. It is as strong as steel. It is ideally elastic, not exhibiting plastic deformations up to the yield point, unlike metals. The E-modulus may be as large as 190 GPa depending on crystal orientation, and the yield strength is about 7 GPa. With corresponding doping concentration (boron, phosphorus) the resistivity can be changed by eight orders of magnitude between $10^{-4}$ and $10^{8}$ ohm cm. This allows structures such as conductive plates or comb fingers to be manufactured ([34]). Silicon has a diamond structure based on a cubic crystal lattice and exhibits pronounced orientation dependent properties like piezoelectricity, piezoresistivity and piezo-Hall effects ([51]).

![Silicon orientation on wafer](image)

Figure 1. Silicon orientation on wafer

Silicon monocrystals are grown as cylinders. The wafers for Complementary Metal Oxide Semiconductor (CMOS - the basic technology for manufacturing integrated circuits) and bulk micromachined devices are usually cut out of the cylinder along one of the six planes of the crystal lattice as shown in Figure 1. To identify the lattice orientation a so called wafer flat is introduced serving as reference orientation. The flat lies in the diagonal plane of the cubic lattice as shown in Figure 1, left (The numbers in the Figure are the so called Miller indices which are used to describe the orientation of
crystal axes and planes.). A device on the wafer that is oriented perpendicularly to the flat has an angle of 45° with one of the cubic lattice planes. Stress dependent material parameter matrices are related to a stress impact oriented perpendicular to the cube planes. For orientations which differ from this basic configuration the corresponding parameters must be calculated by rotating the material matrix.

Polycrystalline silicon or ‘polysilicon’ for short, which is made up of small single-crystal domains of silicon (grains), has similar properties and is the most popular building material for Surface Micromachined devices (see section 4.4).

Mechanical and electrical properties of polysilicon are slightly inferior compared to monocrystalline silicon but are very close to an isotropic; thus, the material is much easier to handle than monocrystalline silicon.

3.1. Mechanical Transducers

Mechanical transducers convert mechanical forces such as pressure or inertial forces into deflections and/or the corresponding stress and strain. They belong to the standard repertoire of MEMS transducers and can be implemented in nearly all technologies.

The most frequently used mechanical transducers are cantilever beams, linear and torsional springs, elastic bridges, composed suspensions and diaphragms which are now sketched one by one.

A cantilever beam may serve as an example for a simple force-to-deflection or force-to-stress transducer. The notations for a bend beam are given in Figure 2. The beam is fixed at the origin of the coordinate system.

Cantilever beams in MEMS are usually long and wide, but not high. Such beams are mainly compliant (elastic) in the $z$-direction. If $B$ and $H$ are comparable then the bar becomes sensitive to rotation for moments about the longitudinal axis and may act as a torsional spring.

![Figure 2. Bend beam and corresponding coordinate system](image-url)
The spring rate $k_z$ of suspensions is used for the calculation of the force-to-deflection relation. For the cantilever beam it can be derived as (see, e.g., [8])

$$k_z = F_z / w(L) = 3EI_y / L^3 = \frac{1}{4} EB \left( \frac{H}{L} \right)^3. \quad (1)$$

$E$ is the Young’s modulus, which for polysilicon (and silicon) is about 166 GPa; $I_y = \int_S z^2 dS$ is the geometric moment of inertia which in the case of a rectangular beam equals to $I_y = BH^3 / 12$.

If the force is captured by a corresponding stress measurement, the stress must be known. Stress is the force per area related, in general, to the planes of infinitesimal small cubes. Normal stresses act orthogonal to a cube’s plane, shear stresses act in plane and cause a deformation of an initially quadratic face, i.e. shear strains (see, e.g., [53], [54]).

For the cantilever considered here the longitudinal stress at location $x$ is

$$\sigma(z - H/2) = - (L - x)(z - H/2) F_z I_y \quad (H - thickness \ of \ the \ beam).$$

It is positive on the lower surface ($z = 0$), which corresponds to tension, and negative on the top surface (compression). The maximum stress is located at the anchor point $x = 0$. Therefore, stress-sensitive piezoresistors should be positioned nearby.

If the cross section of the beam is not ideally rectangular, but with inclined sidewalls, the cross-coupling spring rate $k_{yz} = F_z / \nu$ which characterizes the parasitic deflection $\nu$ in the $y$-direction, is proportional to the sidewall angle.
Mainly due to large temperature gradients during production and to the non-identical temperature coefficients of the different layers polysilicon films often feature non-negligible ‘frozen’ or residual stress $\sigma_0$. Special annealing is used to reduce such stress. The residual stress changes the force balance in beams. This leads to changes in the spring rates. Bulk silicon is basically free from residual stress and therefore often better suited for high-performance applications.

Elastic suspensions in MEMS are usually composed of elastic bars. For instance, a proof mass may be elastically suspended on a rigid frame as illustrated in Figure 3 above. Two fixed-guided beams carry the proof mass on one of their ends and are fixed to an outside frame.

Fixed-guided beams are exposed not only to transversal but also to longitudinal stress that change with temperature and are subject to asymmetries.

Folded beams as in Figure 3 bottom avoid such problems and are usually preferred.

A bridge is basically a double clamped beam where the ends at $x = 0$ and at $x = L$ are fixed. The load is applied between the ends. The double clamped beam – if excited by a force in $z$-direction – is a beautiful resonator like a violin string. Similarly to a cantilever beam with residual stress the properties of the double clamped beam depend on additional longitudinal stress that may be caused by axial forces. If, for instance, both supports are pressed towards each other, compressive stress develops inside the beam, and tensile stress – for pulling apart both supports. The action of axial loads can be treated as a change of the spring rates for the $z$-deflections. Consequently, the resonance frequencies of the beam change. This effect is used for designing resonance accelerometers and pressure sensors.

Most suspensions in MEMS are composed out of parallel and serial spring connections of beam-like springs. For parallel connections of two springs the total deflections are equal and the spring rates add up. In contrast, for serial connections the forces on the springs are equal, but the displacements add, so that the inverse spring rates sum up.

![Figure 4. Some typical linear and torsional suspensions (after [32])](image-url)
If a rectangular plate that should deflect in one of the in-plane axis, say the $y$-axis, is suspended by four identical springs on the surrounding frame as illustrated by Figure 4, parts (a) to (d), the resulting spring rate of the suspension is four times the spring rate of a singular spring. Accelerometers which are sensitive in the $y$-direction are usually equipped by such proof-mass suspensions which restrict the deflections in the $x$ and $z$-directions but favor $y$-deflections. Part (e) of Figure 4(a) shows a suspension that can support $x$- and $y$-deflections to an equal extend.

In Figure 4(b) some torsional suspensions are presented. As shown, stress-compensating loops are often built into the springs in order to prevent additional longitudinal stress.

Thin diaphragms are the basic elements of MEMS pressure sensors. The displacement of the diaphragm or the stress developed at certain locations are used as indicators for the acting pressure $P$ or, more precisely, for the actual pressure difference (net pressure $\Delta P$).

Most of the diaphragms in MEMS are circular, quadratic or rectangular. If a circular diaphragm with constant thickness $H_D$ and radius $R_D$ is positioned in the $x$-$y$-plane, the displacement in $z$-direction, $w(r)$, at the distance $r$ from the center of the diaphragm satisfies the relation (e.g. [62])

$$w(r) = \frac{PR_D^4}{64D} \left(1 - \frac{r^2}{R_D^2}\right).$$

(2)

where $D$ is the so called flexural rigidity of the diaphragm: $D = EH_D^3/12(1-\nu^2)$; $\nu$ – the Poisson ratio and $\rho$ – the density. $w(0) = PR_D^4/64D$ is the maximal deflection in the center of the diaphragm.

Pressure sensing can be performed by capacitive measurement of the (averaged) deflection; for instance, in the middle of the diaphragm or over the full area, or by piezoresistive measurement of the produced stress.

There are two components of the stress: in radial direction, $\sigma_r$, and in tangential direction (in-plane of the diaphragm but orthogonal to the radius), $\sigma_t$. Due to symmetry the shear component $\sigma_{rt}$ is always zero.

It can be shown (e.g. [8]) that the absolute values of the stresses are maximal at the edges $\sigma_r(R_D) = \sigma_t(R_D) = \pm \frac{3R_D^2}{4H_D^2} P$ and reduce to $\sigma_r(0) = \sigma_t(0) = \frac{3R_D^2}{8H_D^2} P(1+\nu)$ in the middle. An optimal pressure measurement should use both stresses, $\sigma_r$ and $\sigma_t$, at the diaphragm boundaries.
Similar considerations can be made for rectangular or quadratic diaphragms. For a quadratic diaphragm with side length $2L$, the maximum stresses arises at the middle of the edges. Consequently, the middle points of the diaphragm edges are predestined for the positioning of the piezoresistors.

As for double clamped beams the resonance frequency of a diaphragm depends on the pressure load. This dependency is used for the design of resonance pressure sensors.

### 3.2. Stress- and Strain Transducers

Stress and strain transducers convert stress and strain into electrical signals or vice versa.

#### 3.2.1. Piezoresistors

Piezoresistors are excellent stress sensors and are used frequently in MEMS devices, especially in mechanical and inertial MEMS. Piezoresistors change their resistivity depending on value and orientation of the acting stress. The relation between resistance changes and the acting stresses are characterized by the piezocoefficients $\pi(i, j)$.

In bulk micromachined MEMS the piezoresistors are usually realized by selective doping of bulk silicon, which creates junction-isolated resistors. In this case the piezoresistor is exposed to the stress acting at the location of the resistor. Exponentially growing with temperature leakage currents through the junction diodes are an inherent drawback. The temperature coefficient of such devices is very high exceeding by far the stress-induced resistance changes and makes temperature compensation necessary.

The model of a typical thin piezoresistor is shown in Figure 5.

![Figure 5. Coordinate system and dimensions of a thin piezoresistor](image-url)
If there are no contacts on the sidewalls of the resistor, no current can flow in the \( y \)-direction. Assuming further a very thin resistor, the stress components can develop in the surface plane only so that \( \sigma_{zz} = \sigma_{yy} = \sigma_{xz} = 0 \) (The stress \( \sigma_{ij} \) is the stress in the plane \( x_i = \text{const} \) which acts in \( x_j \) direction.) In many applications also the shear stress in the \( x-y \)-plane, \( \sigma_{xy} \), can be neglected so that only the longitudinal and transverse stresses determine the resistance changes. For many designs one of this stresses is dominant and, hence, can be directly captured by the piezoresistor.

The large temperature dependency of the resistance of a piezoresistor in the absence of stress, \( R_0(T) \), makes temperature compensation techniques mandatory. An elegant method can be derived using the dominance of one of the piezo-coefficients of p-doped silicon over the remaining others. If, for instance, on a beam that is oriented parallel or perpendicular to the wafer flat (see Figure 1), two piezoresistors are positioned, one, \( R_1 \), oriented parallel to the flat and the second one, \( R_2 \), perpendicular to it, then their resistance changes are approximately equal but have opposite sign. As can be shown (see, e.g., [32], Chapter 1) the corresponding resistance changes are proportional to the difference of the longitudinal and transversal stress within the piezoresistor.

Arranging two pairs of such orthogonal resistors in a full Wheatstone bridge as illustrated in Figure 6 the output voltage of the bridge is proportional to the described stress difference. It does not depend anymore on the strong temperature-dependent zero-stress resistance \( R_0 \) of both piezoresistors.

An alternative way to reduce the large temperature sensitivity is to measure the lateral voltage of the resistor, which requires a four-contact arrangement. Such a four-contact design resembles a Hall sensor and therefore is often called ‘Hall-like’.
Similar arrangements as for beam just discussed can be also used, for instance, for measuring diaphragm stress in pressure sensors.

The piezoresistive effect of polysilicon is less developed than in silicon, but it is still of the same order. However, a big advantage of polysilicon is the possibility to deposit it via a thin electrically isolating silicon oxide on the substrate. This avoids the dangerous leakage currents. The temperature dependency of the resistor is therefore much smaller than that of doped silicon.

3.2.2. Piezoelectric Transducers

Piezoelectric devices produce charges under applied stress (direct piezoelectric effect) and deform under applied electrical fields (inverse or inverse piezoelectric effect). The direct piezoeffect is illustrated in Fig. 7(a).

![Figure 7. The Piezoelectric effect and a piezoelectric sensor](image)

The stressed piezoelectric material generates charges $Q$ at the surfaces, which are collected by the two electrodes, and therefore create a voltage $V = Q/C$ or a current $i = \dot{Q} = dQ/dt$. $C$ is the capacitance between the electrodes. Conversely, if a voltage $V$ is applied to the electrodes, the piezoelectric material undergoes a deformation according to the produced stress/strain. Thus, a piezoelectric sensor measures the generated charges or currents while the actuator transforms the applied voltage into a deformation of the piezoelectric material.

The separation of charges under stress and the deformation of materials under electrical fields have the same root cause: the non-centrosymmetric charge distribution within a crystal lattice which leads to the creation of electrical dipoles under stress. Silicon has a cubic symmetry and, therefore, is not piezoelectric.

The integration of natural piezoelectrics like quartz into silicon-based MEMS is difficult. Hence, artificial piezoelectric materials like ferroelectrics with pronounced piezoelectric properties are preferred. The most often used materials are PZT (lead zirconate titanate) and Barium titanate.
Ferroelectric materials usually are manufactured as ceramics by sintering fine powders. Within the MEMS environment the piezo-ceramic materials can be deposited onto silicon carriers by sputtering, sol gel deposition (manufacturing of non-metallic, anorganic or hybrid polymer material starting from colloidal dispersion – the sol), screen-print processes and others.

Some polymers also feature high piezoelectric constants. The best known representative is PVDF (Polyvinylidene fluoride).

A typical piezoelectric sensor is illustrated in Figure 7(a). If only a vertical or longitudinal homogeneous stress, $\sigma_3$ or $\sigma_1$, is applied to the piezoelectric then the generated charge is proportional to these applied stresses. The case of longitudinal stress is typical for a thin bend beam with dominant longitudinal stress which can be measured by a piezoelectric sensor on top of the beam. The corresponding arrangement with two electrode layers is shown in Figure 7(b). The thin, lower electrode, which is tightly connected to the beam on the bottom and the piezoelectric on the top, guarantees a good transfer of the beam strain into the piezoelectric.

The unavoidable shunt resistance to the working capacitance between the collecting electrodes is responsible for dissipation of a static charge. Hence, if a constant strain is applied, the generated free charges will inevitably be lost over time by leakage currents. However, the present IC- and packaging technologies allow us to reduce the leakage currents down to values which guarantee hold times for the charges of minutes up to hours. For most of the practical applications this is fully sufficient.

If a voltage $V$ is applied to the electrodes covering the top and the bottom of a piezoelectric material as shown in Figure 7 the material acts as a piezoelectric actuator. Vertical and longitudinal strains develop and are transferred to the beam (e.g. [64]). The longitudinal strain bends the beam. A harmonic voltage $V = V_0 \cos \omega t$ (with $\omega = 2\pi f$) applied to a relative thick piezoceramic which is placed on an elastic beam can drive the beam into resonance.

However, even for high-performance piezoelectric materials the elongation of a 10$\mu$m long and 1$\mu$m thick piezoelectric is about 10 nm/V only. Therefore, the use of the inverse piezoelectric effect for MEMS actuators often requires relatively high voltages up to dozens of $V$. Hence, piezoelectric MEMS-actuators are especially well suited for nano and sub-nano technologies like scanning probe microscopy.

3.3. Capacitive Transducers

Capacitive transducers are easily customizable links between geometric displacements (e.g. deflections of moving masses in inertial sensors or displacements of diaphragms in pressure sensors) and electronic signal processing. Unlike piezoresistors or piezoelectric sensors they do not require materials that are unusual for CMOS fabrication. They enjoy wide popularity due to their insensitivity to temperature changes and low drift which allows us to design high performance products with very small offset- and sensitivity changes over the temperature range. In-plane and out-of-plane capacitance sensing and
actuation are possible. A great variety of electronic input stages like charge amplifiers, transconductance stages, switch-capacitor devices and embedded sigma-delta converters are at the disposal of the system designer for various sensitivity levels and various requirements of power consumption and size (e.g. [32]-Chapter 6, [65]). Resolutions down to the sub atto Farad region ($< 10^{-18} F$) are typical for modern MEMS.

Capacitive transducers comprise capacitive sensors and electrostatic actuators. The basis of all capacitive transducers is the plate capacitor as shown in Fig. 8(a), which usually consists of two in-plane electrodes or is arranged as a connected and interdigitated vertical comb structure.

The capacitance $C$ of the plate capacitor is given by the well-known equation

$$C = \varepsilon \frac{A}{D} = \varepsilon \frac{LB}{D}$$

where $\varepsilon$ is the electrical permittivity, which in vacuum, dry air or inert gases has the value $\varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$, and $A$ – the area. In MEMS the gap between the electrodes, $D$, is small in comparison to the lateral dimensions $L$ and $B$. This makes them very sensitive to tiny changes of distance which happen if one of the electrodes is elastically suspended and can shift correspondingly as illustrated by the example in Figure 8(b).

Any capacitor with a fixed and a movable electrode acts as sensor and actuator at the same time. In particular, when a voltage is applied to the electrodes of a sensing capacitance, a charge is created, which is proportional to the capacitance value. This charge can be sensed by electronic means. Simultaneously, the applied voltage creates a force which may displace the movable electrode and consequently falsify the initial capacitance value. Capacitive sensing requires care in order to avoid or to compensate such effects.
Electrostatic forces between two electrodes limit the region of stable movements (e.g. [55]). For instance, if one of the plate electrodes is movable in \( z \)-direction as in Figure 8(b), the capacitance \( C_p \) is given by

\[
C_p = \frac{\varepsilon_0 A}{D + z},
\]

where \( z \) is the deviation from the nominal distance \( D \). As can be shown the maximal stable deviation is given by \(-z < D/3\), i.e. by one third of the gap. For larger deviations the movable plate becomes instable, moving towards the fixed plate, where it is stopped. This effect is called Pull-In effect. An undesired contact between both electrodes may cause disastrous sticking effects. The mechanical operating range of a capacitive sensor should be much less than the stability limit \( z_{\text{op max}} \ll D/3 \). However, there are exceptions such as the digital micro-mirror within the DMD array of Texas Instruments, where sticking is avoided by reducing the contact area down to small tips and where the full displacement range for actuating the mirrors is exploited.

Most capacitive sensors are designed as capacitor pairs in order to enable differential measurement. For instance, if two identical plate capacitors transform the movement of a proof mass into electrode deflections with opposite directions, \( C_1 = \varepsilon A/(D + z) \) and \( C_2 = \varepsilon A/(D - z) \), a differential measurement delivers an output proportional to the difference \( \Delta C = C_2 - C_1 \approx 2\varepsilon(A/D)z \), \( (z \ll D) \). Bidirectional actuation also requires two capacitances, because one capacitance is able to develop attractive forces only.

There exist various arrangements of paired capacitances. One of them is the tilting-plate capacitor as shown in Figure 9. Two capacitors are rigidly connected by a central beam, which is suspended by two rotational springs. Rotational movements can be sensed very precisely by differential measurement of the capacitor changes. Angular deflections including rotational oscillations can be excited by applying voltages to the right or the left capacitances alternatively.
The so called comb capacitors operate similarly. Figure 10 illustrates a real example of a surface micromachined radial comb capacitor.

![Radial comb structure manufactured in a surface micromachining process](image)

Figure 10. Radial comb structure manufactured in a surface micromachining process

The two rows of interdigitated fingers constitute two capacitors. The fingers act as vertical electrodes. Both caps must be excited by the outer rows of fingers with voltages of different sign in order to perform differential sensing or actuation.

The total acting moment about the out-of-plane axis created by both combs supplied with $V_{1,2} = V_{DC} \pm V_{AC}$ is (see, e.g., [32])

$$M_{\Sigma \delta} = \frac{2}{\delta} C_0 V_{DC} V_{AC},$$

(5)

where $\delta$ is the overlap angle in zero position and $C_0$ – the capacitance in zero-position. For a harmonic excitation, $V_{AC} = V_0 \sin \omega t$ a clean sinusoidal oscillation is generated. By varying the excitation frequency the associated mechanical system can be driven in resonance.

### 3.4. Thermal Transducers

Temperature sensors in MEMS are used to measure gas pressure, gas and fluid flow, masses, thermal conductances of fluids, humidity, chemical species, IR radiation etc. Thermal sensor arrays capture temperature differences or distributions. Many thermal actuators exploit the local heat generation to create temperature gradients. Local cooling, especially for heat-generating parts of a device, is another actuation task.

Thermal transducers include thermodiodes and thermotransistors, resistor and thermistor sensors, thermocouples and thermopiles based on the Seebeck effect and various thermal actuators. The small mechanical actuation caused by the thermal expansion of heated parts is often amplified by mechanical leverages. Heat pumps with
Peltier elements, alone or in arrays, complement the spectrum of thermal transducers. Thermal transducers are present in nearly any kind of MEMS, at least for temperature measurement and control.

### 3.5. Magnetic Transducers

Magnetic sensors capture between one and three spatial components of an external magnetic field \( \vec{B} \). Magnetic actuators generate a Lorentz force as a result of the interaction between a current and a magnetic field. The interaction of an external magnetic field with movable magnetic materials also generates magnetic forces. Finally, deformations of magnetostrictive materials subject to magnetic fields are another effect exploited to design magnetic actuators.

Galvanomagnetic sensors such as Hall plates, magnetodiodes and magnetotransistors use non-magnetic material such as doped silicon. As mentioned in Section 2.6, they have been developed and successfully marketed by using standard CMOS technologies. They also include vertical Hall plates, which are sensitive to an in-plane magnetic field. The combination of horizontal and vertical Hall sensors has allowed us to create 3D magnetic sensors to capture the orientation of the Earth’s magnetic field.

Ferromagnetic magnetoresistors change their resistance depending on magnitude and orientation of the applied magnetic field (anisotropic magnetoresistive – (AMR) – effect) typically by some 3 to 4 %. In superfine sandwich structures made from magnetic and non-magnetic materials the giant magnetoresistive effect (GMR), the tunnel magnetoresistance effect and the colossal magnetoresistive effect have been realized. The three typical resistance changes are in the order of 50%, some 100% and over 1000%.

Magnetoresistive sensors are very sensitive. They are produced in high volumes and found their application in industrial and automotive areas as well as in many consumer applications for position- and angular measurement, for current sensing and for compass-like purposes. GMR and TMR sensors are increasingly used for measurement of low magnetic fields as, for instance, in the case of eddy current sensing or in medicine. Their on-chip realization together with auxiliary electronic components using typical MEMS technology leads to a permanent migration into the MEMS area.

Rare-earth magnetostrictive transducers containing TbFe and SmFe produce large magnetostrictions under low magnetic fields and are well suited for MEMS devices. Magnetically excited microcantilevers coated with an amorphous thin film of the giant magnetostrictive alloy Terfenol-D produce sufficient deflections to be used in valves, micropumps, magnetometers etc. Excitation of magnetostrictive materials by on-chip generated harmonic magnetic fields allows to drive beams or suspended masses into resonance and to sense their change under external DC-fields.

Magnetic actuation is often combined with sensors that measure the results of the actuation. Examples are magnetic field detectors as shown in Figure 11 (see [43]) or magnetic resonant sensors as illustrated by Figure 12 (see [20]).
3.6. Optical Transducers

Optical detectors such as photodiodes, phototransistors, bolometers for radiation power sensing especially in the InfraRed (IR) region and Charge Coupled Devices (CCD) for image detection are predominantly fabricated in microelectronic technologies.

Photodiodes are semiconductor structures well known from classical CMOS technology. Unfortunately, a CMOS photodiode can not be integrated into many
MEMS. For instance, fluidic MEMS very often use non-semiconducting materials like quartz or glass substrates instead of silicon. Special photodiodes such as vertically integrated hydrogenated amorphous silicon photodiodes deposited as detector-array on glass substrate have been developed to overcome this difficulty ([47]). They can be integrated into optical, microfluidic, lab-on-a-chip, chemical and biological devices where photo-detection is needed.

Bolometers and bolometer arrays measure the temperature-dependent resistance change caused by the absorbed incident radiation which heats the bolometer element with respect to the heat sink.

The absorptive element in microbolometers for thermal (IR) cameras is vanadium oxide or amorphous silicon atop a corresponding grid of silicon. Thermal isolation from the environment is a key requirement for high sensitivity. MEMS technologies are used to realize such uncooled microbolometers for IR imaging. The pixels of the sensitive matrix feature a thin absorbing layer suspended above the substrate by narrow thin flexures which reduce the conductive heat loss. The chip is packaged in vacuum in order to eliminate convective heat losses. Such microbolometers are on the market and promise a considerable price drop against cooled devices, expanding the application areas dramatically.

Light emitters in CMOS technologies include light-emitting diodes (LED) based on electroluminescence and a great spectrum of laser diodes based on direct bandgap semiconductors and optical cavities (e.g. Fabry-Perot resonators) surrounding their gain region. Heterostructure lasers as well as vertical-cavity surface-emitting lasers (VCSEL’s) have been developed. They all require CMOS-like technologies and a variety of different materials (e.g. Gallium arsenide, aluminum gallium arsenide, indium phosphide, gallium antimonide). The cointegration in non-CMOS like MEMS is still a costly undertaking.

4. Technologies

MEMS have borrowed their basic fabrication steps from IC-technologies and have extended them towards new etching techniques, micromolding, laser machining, wire electrodischarge machining, diamond milling and others (see, for instance, [21]).

For cost reasons a common use of basic technologies for industrial IC’s and MEMS is the dominant paradigm. Specialized processing steps like machining of quartz are organized in small and relatively cheap fabrication lines completing existing technologies.

Generally, a high degree of compatibility of fabrication steps with microelectronic mainstream equipment and technology recipes is decisive for a successful MEMS-product and its long term advancement. Hence, not only the technical pressure on co-integration of sensors and electronics, but mainly economic facts dictate the indispensable conjunction of MEMS technologies and microelectronics.

4.1. Microfabrication
Despite the use of some non-planar, three-dimensional devices such as vertical bipolar or power transistors, and of stacked devices, the world of IC’s and MEMS is primarily two-dimensional, following the multiple recurrence of film- or layer focused fabrication steps. These involve

- Film deposition (physical and chemical vapor deposition (PVD, CVD), electrodeposition, molding, spin casting, sol gel deposition, etc.)
- Pattern transfer (optical proximity and projection step-and-repeat lithography, direct E-beam and laser write technique)
- Structural change (oxidation, doping, ion implantation, drive in diffusion)
- Etching and cleaning (isotropic and anisotropic wet etching, vapor and plasma assisted dry etching, deep reactive ion etching, planarization, lift off techniques, chemical mechanical polishing, wafer cleaning, ashing).

Microfabrication is aimed at breaking the barriers into the truly three-dimensional world with moving objects, with flowing fluids in channels and rotating wheels in microengines.

The creation of moving objects within planar structures is inevitably linked to the removal of material around the target object. If the target object is embedded into silicon substrate, it can be released by bulk micromachining, by which bulk material is etched away leaving the released structure attached to the surrounding substrate or to layers covering them.

If the target object is a section of a deposited layer or a layer-stack and has to be released from the underlying layer(s), surface micromachining is used to etch away a sacrificial layer under the intended structure. Both techniques are usually complemented at least by the integration of transducer elements. Both techniques can be combined and executed separately or within an IC-fabrication flow. In the last case one is talking of monolithic integration, placing the moving structure and corresponding transducers together with signal processing electronics on one chip.

Deposition and pattern transfer in MEMS coincide with CMOS techniques with some exceptions related to the introduction of new materials. For instance, the requirements of high aspect-ratio MEMS have forced the development of thick photoresists and of the corresponding patterning methods such as LIGA (LIGA – German acronym for Lithographie, Galvanof ormung, Abformung) – a process developed in the early 80’s by the nuclear research center in Karlsruhe in order to engrave structures in layers which are up to some mm thick ([9], [12]). Exposure of the resist was performed not by optical lithography, but by hard X-ray synchrotron radiation. Later a UV based alternative has been developed and is now a part of standard microfabrication processes.

Additional requirements are also related to back-to-front-side alignment, which is typical for bonding different wafers together, or to adjust back-side-structures to front-side patterns on a wafer. A lot of high precision bonding equipment has been developed for such kind of tasks.

4.2. Etching
Etching is the most widely used fabrication step for forming movable MEMS structures, channels and cavities on silicon and glass wafers. It includes the traditional wet etching and modern dry-etching technologies.

The relevant parameters of an etch process are the etch rates within a given material, etch selectivity with respect to other materials such as masking and non-masking layers, the dominant etch direction, and so on.

Isotropic etching has no preferred etch direction – the etching propagates independently of the orientation of the material. During wet etching the substrate with exposed patterns is immersed into a tank with liquid chemicals.

In Figure 13 above the result of isotropic etching of a dielectric layer on silicon is shown. The etching propagates under the etch mask resulting in tapered sidewalls.

A deep isotropic wet etching into the substrate using a very aggressive etchant is illustrated in the bottom of by Figure 13. This is a typical bulk micromachining process. However, for not so strong etchant the different activation barriers related to the different plane orientations in silicon cause orientation dependent etch rates and, correspondingly, an anisotropic etching process.
Isotropic wet and dry etching is a basic release process in surface micromachining (SMM). Figure 14 illustrates the principal flow of a SMM process. An isolation layer is deposited, followed by the sacrificial or spacer layer. Pattern transfer – in order to define anchor regions – is followed by deposition of the structural layer – often polysilicon. The structural layer is then also patterned and the sacrificial layer removed by isotropic etching, so that the structure outside the anchor region is released. To remove the sacrificial layer underetching must be very strong. If the lateral dimensions are large relative to the thickness of the sacrificial layer, long etching times result and the structural layer may be affected due to the limited etch selectivity. A way out that is often used is to introduce etch-holes in order to ease the access to the sacrificial layer.

However, for a long time the main difficulty in SMM has been caused by capillary forces within the small gap between the structural and ground layers. During the long rinse and dry steps ionized water is present within the gap. As drying progresses, the surface tension of the rinse water attracts the microstructure towards the ground layer until stiction occurs.

To release the structure, large forces are needed, which usually destroy the microstructure. This problem has been overcome by gas phase dry etching and by the introduction of anti-sticking agents like hydrophobic coatings, by sublimation drying processes, by temporary stiffening structures, by permanent contact-reducing bumps (dimples) and other means (see, for instance, [3], [45], [49]). Contact reducing dimples as well as antisticking agents and atomic layer deposition are also common for preventing in-operation sticking.
Anisotropic wet etching is a typical bulk micromachining process. The anisotropic behavior is caused by the different surface-orientation-dependent activation barriers of silicon and the corresponding orientation-dependent etch rates. This leads, for instance, to an inclination of 54.74° of the sidewalls of an etched cavity. At convex corners the etch behavior changes rapidly. The exploitation of such effects combined with the implementation of compensating structures by appropriate layout allows us to build a great variety of different geometries including cavities with vertical sidewalls.

Anisotropic wet etching is often used for back-side etching of substrates that are covered on the front side by structural layers in order to form membranes, beams, hot plates etc. Unfortunately, due to the inclined sidewalls the back-side cavity needs a significantly larger footprint than the required structure on the front side.

Dry etching is the result of physical or chemical reactions on a surface in gas or vapor phase. The two basic types are vapor and plasma etching. Pure vapor etching in micromachining is used mainly for silicon etching, especially for release etching in SMM.

Plasma or reactive-ion etching (RIE) is usually initiated by a strong RF-electromagnetic field in a chamber that ionizes the gas, separates the charges and accelerates the active species towards the surface. The etching process is a complicated mixture of chemical etching, ion-enhanced etching, physical etching and deposition of non-volatile materials on sidewalls (sidewall passivation).

Deep reactive ion etching (DRIE) is an enhancement of the simpler RIE process. If the horizontal areas and sidewalls of the etched cavity as shown on the top picture of Figure 15 (b) are covered by films (middle picture), which may result from reactions of etchant gases with erosion products of mask resist, bombardment removes the film on the horizontal areas leaving the sidewall films untouched and ready for the next etch step (bottom). With an appropriate combination of film deposition on sidewalls and its chemical removal, the sidewall protection allows processes with astonishing aspect...
ratios and nearly perfect vertical sidewalls to be designed. The process may consist of many such elementary cycles.

In the early 1990s the German company Bosch patented a process according to the described principle ([24], [38]), which has revolutionized the toolset of microfabrication processes, becoming one of the most important tools in surface and bulk micromachining.

The Bosch process features fast etching rates, small sidewall inclination, very large aspect ratios up to through-etching of a wafer. The repetitive nature of the process leads, however, to small scalloping of between tens of nanometer and fractions of a micron (~0.2 – 0.5 μm), which is usually not critical.

An example of an etched polysilicon comb structure is presented in Figure 15 (a).

### 4.3. Wafer Bonding

Wafer bonding has become an indispensable means for forming MEMS structures and providing zero-level packaging.

In contrast to silicon-on-insulator wafers (SOI), where two silicon wafers are bonded together over the whole area, wafer bonding for building MEMS structures or performing zero-level packaging requires patterned substrates, in which only selected areas around the intended cavities, called bond frames, are bonded together. The wafer-wafer composite constitutes a regular mosaic of dies bonded with their counterparts and containing cavities.

Most of the MEMS structures require a special working environment for protecting fragile structures during final dicing and/or during operation (e.g., pressure sensor diaphragms) or for creating hermetical and vacuum conditions.

Protection is required against particle contamination and mechanical overload, against corrosion and stiction, against material change, e.g., under the impact of water molecules, and against change of the gaseous environment. Zero-level packaging is typical for MEMS, and antedates first-level packaging, which affords a sensor system ready for placement on and connection to a printed circuit board (PCB). Zero-level packaging consists of creating a cavity and electrical connections to the outside world.

A typical zero-level packaging approach is demonstrated in Fig. 16. The sensor is encased by a cavity, formed by a device wafer (bottom) and the top cap-wafer. A special bond frame area has been introduced, where the two wafers are bonded together.

Electrical connections to the outer bond pads can be created. Different materials and layer combinations like aluminum between insulating films are used, some with more than one conducting layer. The resulting surface profile may be uneven. Direct bonding has to tolerate such possible unevenness or the unevenness has to be eliminated before bonding.
There are different wafer bonding processes. The most important are:

- **Silicon direct bonding (silicon fusion bonding)** for Si-Si, SiO₂-Si, Si-glass, glass-glass with superior bond strength and vacuum suitability. The joining forces develop between smooth and hydrated surfaces, that are cautiously pressed together. During the subsequent high-temperature fusion process at about 1000°C they lead to a very strong connection.

- **Anodic bonding (field assisted bonding)** for Si-glass, glass-Si-glass, glass-metal with reliable bonds and some residual stress between the wafers. Glass materials with optimized temperature coefficients like Pyrex (Corning#7740) and Tempax (Schott) are heated up in order to separate the ions of Na₂O. Under an applied electrical field the Na⁺ ions travel to the glass surface, where they are neutralized while the O²⁻ ions move towards the positive silicon wafer, creating a depletion layer and a corresponding strong electrical field. The pulled together wafers form strong Si-O bonds. Some residual stress is unavoidable.

- **Low temperature glass frit bonding** for different materials including special layers such as polyimide and for moderate vacuums. Low melting point glass paste is deposited on the bond frames. During thermal conditioning the solvent is burned out and the glass is pre-melted. The two aligned wafers are than pressed together and the glass heated up to the wetting temperature. The subsequent atomic reactions are similar to the silicon-glass anodic bonding process, forming strong fused regions on both silicon surfaces. The height of the printed structure is about 20 to 30 μm, the bond frame is correspondingly wide.

- **Metallic alloy seal bonding (eutectic, liquid transient phase)**. Eutectic bonding is the most important representative of seal bonding using metallic alloy. During an eutectic bonding process an alloy is created at a temperature that is significantly lower than the melting points of each of the bond partners (for instance 363°C for a silicon and gold alloy). The two Si-wafers with the chosen interface material (e.g.,
preformed gold) are brought into intimate contact and heated up above the eutectic temperature. Here the Au atoms start rapidly to diffuse into the atomic structure of both Si-wafers, forming the eutectic alloy. Subsequently the structure is cooled down. Other materials and optimized interface multilayers may be used in order to improve bond quality.

Eutectic bonding is a low temperature process; it accepts small bondframes and less strong requirements concerning roughness and planarity than direct bonding techniques. Bonding over non-planar surfaces is possible. It does not need high voltages, which may destroy electrostatically embedded structures; outgassing and hermeticity performances are superior in comparison with bonding processes using glass or organic films.

- Polymer bonding (adhesive polymer bonding). Adhesive bonding using polymers like epoxies, polyamides, negative photoresists and so on is a robust, low temperature and low cost process. After deposition the adhesive is exposed to an initial bake to burn out solvents. In the next step the wafers are joined under well defined pressure, and finally the polymer is cured over typically 0.5 - 1 hours. The curing temperature must be above the glass temperature, where the polymer becomes subject to plastic deformation.

Polymers age. The maximal storage temperature is below a few hundred °C. They are outgassing and open for diffusion. Hence, hermeticity or vacuum condition cannot be guaranteed. All this limits their application for wafer-level bonding. However, they are the materials of choice for chip-to-carrier bonding, where simplicity and cost are dominant factors.

- Thermo-compression bonding (solder, soft metal thin films). Solder bonds and thermo-compression bonding of soft metal films are similar to the described adhesive bonding. Deposition of solder or soft metal is possible using preforms or layer deposition and patterning. The mating surfaces have to be pre-coated with material which the solder can easily wet. The bonds are stable and not outgassing, which makes them suitable for hermetic and vacuum packaging.

4.4. Integrated MEMS Processes

An integrated MEMS process is the manufacturing section encompassing fabrication and subassembly of all components including zero-level packaging.

MEMS processes can be divided into

- Bulk micromachining
- Surface micromachining
- Silicon-on-insulator (SOI) processes.

Bulk micromaching and surface micromachining are often used in combination, as for instance in a SOI process. All three processes can be performed independently or in combination with ASIC manufacturing on the same die. In the first case the product is a hybrid component consisting of a MEMS die and an IC die, which then have to be packaged together during first-level packaging.
The advantage of a hybrid approach is the freedom to choose a well suited MEMS technology independently of compatibility with a CMOS process. Furthermore, the yield is usually higher, because the MEMS process can be optimized, and inoperative MEMS or ASIC dies will not be assembled together as is the case of MEMS-ASIC-cointegration.

Bulk micromachining is preferred if large and stress-free moving structures are needed. Surface micromachining is a CMOS-like layering technique as illustrated in Figure 14. The favored material is polysilicon with film thicknesses between fractions of a micron and several microns. Extensions of up to some ten microns are popular.

![Diagram of moving structures in SOI](image)

**Figure 17.** Creation of moving structures in SOI

The principal sequence of a SOI-MEMS process is illustrated by Figure 17. The starting SOI-material with its thin insulating silicon oxide layer is subject to a DRIE process, for instance, to the Bosch process. Deep trenches down to the isolating oxide are formed. Then the sidewalls have to be passivated in order to prevent side-wall etching during the next etch steps. A RIE process is normally used to open the buried oxide within the trenches. Through these openings an isotropic etch step is added in order to remove the Si-material behind the oxide layer and thus to release the moving structure. The moving structure is always connected by suspensions with the surrounding silicon.
SOI-MEMS combine the advantages of bulk and surface micromachining: superior material properties of crystalline silicon, with low tolerances and basically no residual stress, respectable vertical dimensions and correspondingly large proof masses, freedom in shaping the structures within the $x-y$ plane, and, last but not least, high degree of CMOS compatibility.

The integration of MEMS processes into a CMOS flow can be classified according to the location of MEMS fabrication within the CMOS process ([6]):

- Pre-CMOS
- Intra-CMOS
- Post-CMOS.

The variety of CMOS-MEMS processes is exemplified, for instance, by 60 different approaches found in the year 2005 in the literature, and summarized in [7].

4.5. Packaging

First level packaging (FLP) or simply packaging of MEMS is a decisive step of MEMS manufacturing. During packaging the MEMS die is integrated into a package which has to protect the MEMS structure as well as the signal processing elements. For some application classes such as implanted medical sensors the biocompatible package has to protect the human body from toxic reactions or infections.

The package process includes all assembly steps between wafer finishing and final encapsulation such as dicing, die separation, die attach, interconnect between dies, connection to the outside connectors, and encapsulation.

One of the most difficult problems in MEMS packaging is to avoid stress acting on the often very stress-sensitive MEMS die. A careful choice of the materials with respect to their temperature behavior and an optimal geometric design is mandatory and usually supported by simulations using finite-element (FEM) or boundary-element (BEM) methods.

MEMS packaging uses the techniques developed for IC packaging (see, e.g., [27], [63]). Ceramic, metallic and plastic packages have been adapted. However, many MEMS devices, in particular with optical, chemical or mechanical access channels to the outside world require highly specialized solutions. Nevertheless, the infrastructure of the IC-packaging industry is an important basis for a cost-efficient packaging, especially of such MEMS-types for which no mechanical contact to the environment is required, as in case of field measurements (e.g., magnetic, temperature and inertial field measurements). Leading packaging companies like ASE (Korea), Amkor, Carsem, Kyocera and others have extended their portfolio towards such solutions.

MEMS packaging is generating high costs and is often decisive for reaching a given target specification in time ([5], [27], [29]). A common root cause is the huge variety of combinations between sensors/actuators and application conditions, which up to now, has prevented a higher standardization level.
Plastic packages are usually cheaper than ceramic packages, and despite their inferior thermal and stress-creating properties are preferred for high-volume applications. In both cases the flexibility of packaging is limited by very high tooling costs for nearly any geometrical change, and by insufficient material characterization.

A common problem is related to the impossibility of directly testing the package performance with respect to the required sensor functions. Usually, the ultimate impact of package parameters on function and reliability can be revealed only by exhaustive tests and qualification of the final device. Thus, package modifications are time consuming and costly.

MEMS packages can be divided into cavity packages and overmolded packages. In cavity packages the dies are in mechanical contact with the carrier at their ground plane only. Thus, the sensitive MEMS structures may remain open, provided they are temporarily protected during dicing and the assembly is performed under highly clean room class conditions. Overmolded packages create material contact around the entire MEMS die, hence requiring appropriate robustness. In Figure 18(a) a cavity-type ceramic package is shown, while Figure 18(b) illustrates an example of an overmolded small outline IC (SOIC)-type package.

![Figure 18. Examples of cavity type and overmolded packages (after [32])](image)

Clearly, in plastic packages the different temperature coefficients during assembly including the curing process of the mold material as well as during operation are a root cause for stress acting on the MEMS die. In order to mitigate the stress impact the more sensitive MEMS die is sometime covered by highly elastic Silicon gel. An alternative to cavity-like ceramic packages are plastic open-cavity packages which are based on premolded open Liquid-Crystal-Polymer (LCP) cases that are sealed after assembly by an appropriate lid. Contrary to ceramic packages they can never be hermetic.

5. MEMS – Operating Principles

The multidisciplinary nature of MEMS is reflected by a countless number of domain- and application specific solutions. This allows here to only touch upon some of the basic operating principles. The examples are chosen in order to get a first insight into
typical approaches in combining application tasks, transducer principles and technologies.

Not all areas can be presented in a balanced manner: some of them such as magnetic MEMS have been covered by Section 3.5; others like BioMEMS are so broad and need a fundamental knowledge of bioengineering that they exceed the scope of this chapter.

5.1. Pressure Sensors

MEMS pressure sensors are based on thin micromachined diaphragms. An applied net pressure (pressure difference) deflects the diaphragm creating stress, as described in Section 3.1. The stress at well defined locations is sensed by piezoresistors, or the deflection is captured capacitively.

There are basically two types of pressure sensors. The first is based on a diaphragm separating a closed, hermetic cavity with vacuum or gas fill from the outside world as shown in Figure 19(a). In the second type two access channels allow a differential pressure measurement as shown in Figure 19(b). The sensor has contact to two external spaces with different pressure levels.

If the sensor cavity is evacuated down to vacuum level the sensor measures the absolute pressure. For fill gases like air at atmospheric pressure levels the sensor is called a pressure gauge. Since the measurement range is usually around the reference pressure, the intrinsic sensitivity is larger than for a absolute pressure measurement.

5.1.1. Pressure Sensor Packaging

A hermetic reference cavity can be created by zero-level packaging of the diaphragm structure or by first-level packaging. A hermetic first-level package is illustrated in Figure 20. The stainless steel cap is sealed hermetically to the ceramic carrier, thus providing a hermetic cavity.

Such a robust configuration is quite expensive. The main drawback is the stress transfer from the package carrier to the diaphragm, which directly leads to a temperature dependent offset shift. Hence, an intermediate stress buffer in form of a glass or silicon
support chip with similar temperature coefficients is inserted between sensor and carrier to decouple package and sensor mechanically.

A great variety of various other stress decoupling constructions are known ([10]).

![Hermetic first-level package](image1.png)

**Figure 20. Pressure sensor with hermetic first-level package**

![Premolded package](image2.png)

**Figure 21. Pressure sensor in premolded package**

However, for high volume applications, especially in less aggressive environments the plastic package is highly desirable. In this case the cavity must be created during zero-level packaging where the sensor is bonded together with a thermally matching silicon (or glass) wafer. A typical approach is shown in Figure 21. The zero-level packaged sensor is die-bonded by low-stress adhesives to the ground plate of a premolded cavity package. To avoid corrosion and degradation the bondpads and connecting wires outside the MEMS die must be protected. Usually this is achieved by coating the whole
sensor plus interconnects with a highly elastic silicon gel or Parylene polymer. The coat material transfers the outside pressure to the diaphragm. The structure is covered by a robust metal cover having a pressure access port in the middle.

5.1.2. Sensing Pressure

Pressure sensors are based on a great variety of diaphragm geometries and transducer locations. Two basic configurations are shown in Figure 22, where for space reasons both arrangements are placed on one diaphragm.

On the left side of the diaphragm a Wheatstone-bridge-type structure based on p-doped Si and placed at the middle of the left edge is shown. It should be noted that placing two horizontal piezoresistors in the middle of the upper and lower edge and two vertical piezoresistors at the middle of the left and right edge of a quadratic diaphragm gives the same results. A Wheatstone bridge in the center of the square has approximately half the sensitivity at the edges.

Alternatively to the Wheatstone bridge, the Hall-like piezoresistor can be used, as in Motorola’s Manifold-Absolute-Pressure sensor ([1]). The transducer is placed in the middle of the diaphragm edge as shown in Figure 22 on the right side. In practice, the sensitivity of the Hall-like element is slightly smaller than that of a Wheatstone bridge.

Considering that the stress concentration within a diaphragm can be increased by appropriate sculpturing, a variety of diaphragms and corresponding patterns for piezoresistor positioning exist. An example is a two-island diaphragm as schematically shown in Figure 23. In the figure the deformation pattern on the upper surface is indicated (see lower side-view). If two y-oriented piezoresistors are placed on the diaphragm’s edge and at the opposite perimeter of the island, their stress-induced
changes (in opposite directions) can be made equal by appropriate gap- and position
design. Hence, they are again effective building elements for a Wheatstone bridge.

Bulk micromachined diaphragms have large back-side openings and are prone to
breakage during handling. In surface micromachined pressure sensors the cavity is
formed by deposition of polysilicon or silicon nitride over a sacrificial layer. The
patterned sacrificial layer is removed via etch openings that are sealed in a subsequent
CVD deposition step.

Figure 23. Two island diaphragm for pressure sensors

Figure 24. Principle of a surface micromachined pressure sensor
Figure 24 illustrates the considerably reduced dimensions of such sensor. The diaphragm may be thinner and therefore smaller than for bulk micromachined diaphragms. Capacitive sensing as well as on-chip processing of the poly-Si piezoresistor-output signal is easier to integrate.

The most sensitive pressure sensors are resonant sensors. A resonator with stress-dependent resonance frequency is implemented into the diaphragm or mechanically coupled in such a way that the stress is transferred to the resonator. The same principle is used for resonant accelerometers and will be presented in Section 5.2.1.

5.2. Inertial Sensors

Inertial sensors are based on moving masses. Most of them are elastically suspended rigid bodies which are subject to the impact of inertial forces. They are also exposed to damping forces which are the result of the interaction of a moving body with a surrounding gaseous environment and with internal frictional effects (structural damping). Structural damping is usually orders of magnitude less than surface damping and becomes important under vacuum conditions only.

In inertial sensors slide and squeeze damping are dominant. Slide damping occurs at the surface of a body sliding through a gas; squeeze damping takes place if two surfaces that are facing each other are moving to and from each other. Here one surface belongs to the body and the other usually the substrate.

In both cases the damping forces are proportional to the body’s velocity and reduce with falling cavity pressure.

5.2.1. Accelerometers

The simplest accelerometer is a spring-mass system which is sensitive to accelerations in one direction only (1D accelerometer). Figures 25(a) to 25(c) illustrate various principles. The linear spring-mass accelerometer transforms x-accelerations into x-deflections; the torsional accelerometer converts linear accelerations into rotational deflections and the angular accelerometer conveys angular accelerations into angular deflections. All three systems have one Degree Of Freedom (DOF) and satisfy the same type of differential equation. For example, the proof-mass deflection of a linear spring-mass accelerometer obeys the relation

\[ m\ddot{x} + c\dot{x} + kx = F = ma_x + N_B, \]  

where \( m \) is the mass, \( k \) – the spring rate of the suspension; \( c \) – the damping coefficient and \( a_x \) – the accelerations in \( x \)-direction.
The damping force $cx$ has a stochastic part $N_B$ stemming from the probabilistic nature of the particle collisions with the moving body (Brownian noise). The Brownian noise is a limiting factor for a high signal-to-noise ratio (SNR) when it starts to exceed the electronic noise.

The damping coefficient, $c$, determines how the accelerometer reacts to a step-like acceleration. Various types starting from very slow reactions and ending with oscillatory deflections are possible. A more or less optimal reaction is achieved for critical damping, $\delta = c/2m = 1$, where the output follows the step function without any overshoot.

Very often accelerometers are embedded into a feedback loop. This has the big advantage that keeping the deflection close to zero reduces the operational stress and the resulting wear and fatigue within the suspensions. It improves the linearity, reduces possible hysteresis and may help to establish a compromise between mechanical sensitivity and transfer behavior.

However, feedback needs actuators. Piezoresistive accelerometers do not offer such a possibility. In contrast, capacitive accelerometers can easily be equipped with appropriate actuators. Capacitances are intrinsically nonlinear (Section 3.3). Special techniques such as Sigma-Delta conversion are exploited in order to linearize the feedback loop (e.g., [35], [37], [41], [52]). They are also advantageous with respect to implementation friendliness (size, linearity and power consumption) for other control loops.

Capacitive accelerometers are often fabricated using surface micromachining which leads to smaller size. This is why capacitive accelerometers have gained great popularity among the high-volume products. However, due to the larger moving masses bulk micromachined or SOI-based capacitive accelerometers can be fabricated with lower resonance frequencies $\omega_0^2 = k/m$ and, hence, with larger sensitivity. They are superior for high-sensitive, low-g applications.

Piezoresistive accelerometers use the same sensing principles as considered for pressure sensors (Section 5.1). A large proof mass is usually suspended by a single beam or
beam pair on one side or by one or two beams on each side. A z-acceleration forces the beam to bend in z-direction, and the induced beam stress can be captured by one or two appropriate Wheatstone bridges. Multiple beam suspensions are used mainly to suppress cross-sensitivity against in-plane accelerations.

Piezoelectric accelerometers allow a smooth feedback control. Not only bulk micromachined versions exist, but also small surface-micromachined prototypes (e.g., [17]).

Resonant accelerometers are frequency-modulated sensors. Due to their high sensitivity and large dynamic range they are very attractive. The frequency output provides a smooth interface to digital signal processing and a high signal-to-noise-ratio. In Figure 26(a) an example of a resonant transducer – the so called double-ended tuning fork (DETF)– is shown (see, for instance, [50] and [60]), which in Figure 26(b) is embedded into an acceleration-sensitive construction ([58]). If the proof mass is accelerated it creates a tensile force on one of the DETF’s and a compressive one on the other. The two clamped beams within a DETF are excited by the inner combs, and the amplitude of the vibration is captured by the two sensing combs.

Figure 26. Resonant accelerometer

Since the resonance frequency of the clamped-clamped beams depends on the applied axial forces $F_N$, both resonators are driven into their resonances by an appropriate phase-lock loop. The frequency difference is proportional to the applied axial forces and, hence, to the acceleration. Typical resonance frequencies are in the range of some hundred kHz to some MHz. Sensitivities of some dozen Hz per g-acceleration can be easily realized.

Sophisticated leverage constructions have been designed in order to further increase sensitivity, to reduce cross-sensitivity and to simplify the technological effort.

Tunneling accelerometers have found attention due to their superior sensitivity. They exploit the tunneling current between a conducting tip and a plane electrode which nonlinearly depends on a small gap in the order of some 1 $\AA$. The strong nonlinear dependency of the tunneling current on the gap $z$ $I = I_0 e^{-\alpha \sqrt{z}}$ ($\Phi \approx 0.5$ eV – tunneling barrier) makes an operation in closed loop mandatory (see, e.g.
Sometimes the tip-carrying beam is split into a slowly controlled set-beam and a tracing fast beam.

Due to the lifetime problems that are caused mainly by the erosion of the tunneling tip, tunneling accelerometers did not yet find broad applications despite their superiority for high precision measurements.

Convective and bubble accelerometers use heat convection in gaseous or liquid media. Convective accelerometer consists of a hermetically encapsulated cavity that is heated in the middle by a small strip across the bottom. At least two thermopiles or thermistors on the left and on the right of the heater measure the temperature. In absence of acceleration the symmetric convective heat flow causes identical temperatures on both sides of the heater. If acceleration (or inclination) is applied, the emerging asymmetry of the convection flow shifts the temperature distribution in one direction creating a temperature difference at the temperature sensors that is proportional to the acceleration (e.g., [11]).

Similarly, in bubble accelerometers a gaseous bubble shifts under the impact of acceleration forces. The bubble is first created within a working liquid at the activation temperature. Strictly speaking, not the gas bubble shifts, but rather the fluid is displaced giving room for the shift of the gas bubble in acceleration direction. The emerging temperature difference at both sides of the central heater is again a measure for the applied acceleration. Sensitivities in the order of $1^\circ C / g$ have been achieved in commercial available bubble accelerometers (company MEMSIC).

Multi-axis accelerometers are very attractive for game controllers and various platform stabilizing consoles. They can be simply composed by adding two or three accelerometers with orthogonal sensitivities on one chip. Cost pressure has forced the search for more efficient solutions.

One of the possible approaches is to use two or three different weak bending modes of the same spring-mass system which responds to acceleration in two or three directions. 'Heavy' masses are needed to create a pronounced deformation pattern (see, e.g., [4],[14])

However, presently the on-chip combination of 1D accelerometers still dominates the market.

5.2.2. Gyroscopes

The need to capture the relative rotation of a platform like a ship or an airplane has lead to the development of classical gyroscopes. Gyroscopes acquire angular orientations or their changes (rates) using Coriolis forces emerging within a rotating, non inertial system of coordinates. For many applications such as automotive, consumer and biomedicine the earth surface is a sufficiently good approximation of an inertial system.

A classical gyroscope consists of a flying wheel whose large buoyancy together with friction-compensating mechanisms allows us to approximate its rotation as a force-free
movement within an inertial space. The angular momentum conservation principle keeps the wheel-motion unchanged within the inertial system causing a change in orientation of the angular velocity vector within the platform system. By observing this change, the platform rotation angle can be derived.

The relative motion of a body within the platform system of coordinates can equivalently be described by using virtual entities like Coriolis forces or moments. The measurement principle of so called ‘rate’ gyroscopes exploits Coriolis force or moments as a coupling mechanism between platform rotation and mass movements.

The Coriolis force emerges as a vector product of the platform’s angular rate, $\vec{\Omega}$, and the relative velocity $\vec{v}_{rel}$ of a body or its mass element, $dm$, within the platform: $\vec{F}_{Cor} = 2dm(\vec{\Omega} \times \vec{v}_{rel})$. It is orthogonal to both components: to the velocity of the body with respect to the platform and to the rotation vector of the platform. Its direction can be determined using the right-hand rule. Analogously, Coriolis moments are generated by angular movements $\vec{\omega}_{rel}$ of a body relative to the platform and the platform’s angular rate: $\vec{M}_{Cor} = 2(\vec{J}^D \vec{\Omega} \times \vec{\omega}_{rel})$, where the matrix of the dyadic moments $\vec{J}^D$ has coefficients $J^D_{ij} = \int \rho_i \rho_j \frac{dv}{J}$. The $\rho_i$ are the coordinates of the radius vector of a mass element $dm$ of the moving body, where the center of the coordinate system coincides with the body’s center of gravity (COG) (see [32]).

In rate gyroscopes the relative velocity or – if oscillatory – its amplitude is kept constant and, thus, a Coriolis force proportional to the platform’s angular velocity is created. By measuring deflections caused by the Coriolis force, the angular velocity can be determined. Correspondingly, such gyroscopes are called ‘rate’ gyroscopes.

In contrast, ‘angular’ or ‘rate integrating’ gyroscopes try to determine the platform’s orientation keeping the body in ‘free’ motion via feedback control, not disturbing the Coriolis forces, and by measuring the average (integrated) orientation of the body within the platform. Since the orientation of the body within the inertial space remains unchanged, the orientation of the body with respect to the platform reflects the platform orientation within the inertial space. Basically, angular and rate gyroscopes differ in the underlying control- and measurement paradigm, while using the same mechanical construction of an oscillating mass. However angular gyroscopes are difficult to realize and did not gain commercial success.

**Basic design principles of gyroscopes:** In Figure 27 the most common rate measurement principles are illustrated. The traditional spinning-wheel gyroscope – the gyrostate – is based on a flywheel rotating with constant speed and mounted within a gimbal. An orthogonal angular platform rotation, $\Omega_2$, creates a Coriolis moment about the sense axis, $\vec{e}_z$, and rotates the gimbal. The sense moment is measured by applying a compensating torque, whose value provides the desired information on the platform rotation.
Figure 27. Principles of rate measurements based on application of the Coriolis Force: (a) a gyrostat, (b) a vibrating string, (c) a vibrating bar, (d) a tuning fork and (e) a vibrating ring (after [32])

The applicability of this principle for MEMS gyroscopes is limited by the difficulties to create suitable long-living bearings. An alternative is a vibrating string that paved the way into the world of vibrating gyroscopes.

Here, the Coriolis force is not generated by a constant rotation, but by oscillatory movements in form of linear or rotational proof mass deflections. Under the impact of a platform rotation $\Omega$ the vibrating body deviates in the orthogonal plane $\vec{e}_2 - \vec{e}_1$ (see Figure 27(b)). The amplitude of the orthogonal mode is a measure for the applied rate $\Omega$.

Similarly, the tip of a vibrating beam (Figure 27 (c)) deflects in the orthogonal direction under the impact of an axial rotation. Both principles did not gain commercial success as opposed to the tuning fork shown in Figure 27 (d).

Here two tips of a ‘prong’ vibrating in anti-phase are deflected in opposite directions in the $\vec{e}_1 - \vec{e}_2$-plane. Thus, at the common carrier beam a moment is created that can be measured. Of course, also the deflections within the sense-plane reflect the information on an applied angular rate, $\Omega_2$, and can be captured.

Shell-based micromachined gyroscopes – often called wine glass resonator gyroscopes – could take a large part of the automotive market. The principle of such ring- or cylinder rate gyroscopes is demonstrated in Figure 27 (e).

The ring has two in-plane resonances that are ideally at the same frequency and separated in space by 45°, as indicated by the two drawings. Exciting one mode an out-of-plane rate signal generates Coriolis forces that transfer energy into the second mode. The corresponding deflections are measured.

In the period 2000-2010 the most successful structures for building MEMS gyroscopes turn out to be simple flat, rigid proof masses that are particularly well suited for implementation in standard surface or bulk micromachining technologies.
Figure 28. Principle of rigid body MEMS gyros. Reprinted with permission of Cambridge University Press from [32].

Figure 28 illustrates two main methods of operation. The proof mass can be either vibrated in a translational movement, or excited into rotational oscillations forming a vibrating wheel gyroscope.

In the first case the Coriolis force created by an angular rate component, $\Omega \parallel \vec{e}_3\), is directed along the $\vec{e}_1$-axis lying in the platform plane. It causes the plate to additionally vibrate in $\vec{e}_1$-direction provided a suited platform suspension exists. By capturing this sense motion the angular rate component can be calculated.

In case of vibrating wheel gyroscopes a disc which oscillates in-plane about the $\vec{e}_3$-axis is subject to a tilting Coriolis torque about the $\vec{e}_1$-axis. The torque is caused by an angular rate component in $\vec{e}_2$-direction. If an appropriate suspension supports both rotations – about the drive and the sense axes – the sense motion can be picked off and the corresponding rate signal derived.

**Typical properties of MEMS gyroscopes:** Figure 29(a) shows a practical implementation of a $z$-gyroscope, preferably performed in a surface micromachined technology.

Since the two-DOF-system requires a proof mass movable in $x$- and $y$- direction a good guidance along both axes is achieved by using a two-mass system, where the inner sense mass is embedded into an outer frame.

The drive motion comprises the stiffly coupled motion of the frame plus the sense mass, while the Coriolis force forces the sense mass to move with respect to the drive frame in a direction orthogonal to the drive motion. Sense deflections are captured by the inner sensing boxes whose capacitances are formed by the vertical walls of the fixed walls and the walls of the moving sense body. The control of the drive motion requires sensing of the $x$-deflection which is carried out by additional motor-sense combs. The movement of the system is described by
Figure 29. Out-of-plane and in-plane sensitive gyroscopes.

\[
\begin{align*}
(m_D + m_S)\ddot{x} + c_x\dot{x} + k_1x &= 2m_S\Omega_z\dot{y} + F_x + N_{B,x} \\
m_S\ddot{y} + c_y\dot{y} + k_2y &= -2m_S\Omega_z\dot{x} + N_{B,y}.
\end{align*}
\] (7)

\(m_S\) and \(m_D\) are the masses of the sense and the drive frame, \(k_1\) and \(k_2\) – the spring rates in \(x\)- and \(y\)-direction, respectively, \(c_x\) and \(c_y\) – the damping coefficients for the \(x\)- and \(y\)-motions, \(N_{B,x}\) and \(N_{B,y}\) – the corresponding Brownian noise components. The excitation in \(x\)-direction \((F_x = F_{x,0}\cos\omega_0 t; \ F_y = 0)\) generates the Coriolis force \(-2m\Omega_z\dot{x}\). The \(x\)-deflection is the so called drive motion, and the reaction in \(y\)-direction is the sense mode. Therefore, the sense deflection is proportional to the rate signal, \(\Omega_z\).

The Coriolis force \(2m_S\Omega_z\dot{y}\), caused by the sense motion, is small. Its impact is further reduced by stabilizing the drive motion within a feedback loop.

Due to the limited drive forces the structure is excited at resonance. The sense resonator can be adjusted to the same resonance frequency providing maximal sensitivity. However, due to the temperature dependencies of the resonance frequencies and the matching difficulties usually an intended frequency split \(\Delta > (\gg)\Delta\omega_b\) between drive and sense resonance is introduced, which is on the order of 2 to 5%.

Similar structures with decoupled modes are superior to non-decoupled ones, because the suspensions can be built from beams or folded beams that have much lower cross-coupling effects than suspensions with compliance in two directions. Such cross coupling effects are the main source for the so-called Quad-bias – an output signal which is the result of the direct coupling of the drive motion to the sense resonator. For slightly different resonance frequencies of both high-quality resonators it is in quadrature (i.e. shifted by 90°) with the rate output signal. It may exceed it by orders of magnitude; however, being in quadrature with the sense signal allows it to be separated by phase sensitive detection methods.
Vibrating torsional gyroscopes as, for instance, shown in Figure 29(b) have the same mathematical structure. The drive motion is about the $z$-axis. A rate signal about the $x$-axis creates a Coriolis moment $2J_x^D\Omega_x\dot{\theta}$, where $J_x^D$ is the dyadic moment about the $x$-axis, which was defined above. $\dot{\theta}$ is the angular velocity of the body about the $z$-axis and $\Omega_x$ – the platform’s angular rate about the $x$-axis. This Coriolis moment generates a rocking motion of the butterfly-like proof plate. The angle $\theta_y$ is proportional to $\Omega_x$ and is captured by differential measurement of both capacitances underneath the plates.

There exists a huge variety of different gyroscope architectures with two and more DOF. Mode decoupling, bias compensation and resolution are the targets addressed by the different approaches. Decisive performance parameters of gyroscopes are their stability of the zero-rate output, called bias instability, and the rate random walk, which determines the long-term drift. Both are decisive for the possibility to integrate the rate output over a longer time interval and thus to determine an accurate angular change with respect to some initial reference angle. The bias instability causes a best-case error that is limiting the suitability of a gyroscope for navigation purposes. It depends on many tiny effects such as the stability of surface bonds, thermal stability and other, up-to now unknown effects. It seems that bulk silicon is superior in comparison to polysilicon. Bias instabilities as low as 0.5°/hour in all three axes, have been reported for commercial devices ([2]).

A general drawback of linear gyroscopes is their acceleration sensitivity which requires acceleration suppression. Accelerations may be the result of shocks and vibrations or of the loud pressure of audio equipment in cars. In order to reduce the acceleration impact, coupled double-structures are used. They are called tuning forks.

![An anti-phase-driven tuning fork](image_url)

**Figure 30.** An anti-phase-driven tuning fork. Reprinted with permission of Cambridge University Press from [32].
Figure 30 illustrates the principle of tuning fork architectures. Two identical gyroscopes are driven in anti-phase in $x$-direction. Since the Coriolis force depends on the orientation of the velocity vector, a rate signal about the $z$-axis causes deflections in both gyroscopes in opposite $y$-directions. On the other hand, the most dangerous acceleration components in $y$-direction create a common mode displacement. On subtracting the capacitance changes from both sides the acceleration impact is widely suppressed.

Non-planar MEMS gyroscopes have been developed targeting the implementation of beam gyroscopes, of quartz-tuning forks and of ring-gyroscopes. Beam gyroscopes such as shown in Figure 27 (c) have been realized with piezoelectric or capacitive actuators placed on two opposite walls of the beam, and piezoelectric or capacitive sensors – on the other two sides. Additional masses on the beam’s tip have helped to reduce size and performance, especially the robustness against mismatch of driving and sensing resonance frequencies.

Figure 31. Quartz tuning fork and ring gyroscopes

The mentioned high-performance quartz-based tuning forks as well as ring gyroscopes have been very successful in the MEMS market. Figures 31(a) and 31(b) show a little bit more implementation details then the principal drawings in Figures 27(d) and 27(e). The quartz tuning fork of BEI Sensors features a very good bias stability. The length of the sensing element was reduced from initially about 25 mm to around 8 mm. The difficulties in further scaling down the sense element in the end have led to a step by step replacement by other products.

The ring gyroscopes developed by British Aerospace Systems and Equipment together with Sumitomo Precision Products Company Ltd. uses a batch manufactured silicon ring suspended by eight spider-leg springs as shown in Figure 31(b), bottom. The ring is bonded to a glass pedestal and permeated by a constant, vertical magnetic field. The eight isolated spider-legs carry isolated conducting wires that can generate Lorentz forces or sense changes of the magnetic flow.
The external magnet makes further miniaturization difficult. Attempts to substitute magnetic by capacitive transducers did not yet lead to a commercial success.

Similar mode patterns as in ring gyroscopes are used in the emerging bulk-acoustic wave gyroscopes, where a centrally suspended silicon disc is capacitively excited around the perimeter in order to produce bulk acoustic modes. The two main modes are rotated by 30° with respect to each other and coupled by z-rate induced Coriolis forces. Sensing is performed by interposed sense electrodes. The very high resonance frequencies and the diminutive particle displacements predestines this system for mechanical robustness, low damping and low bias.

As in the case of accelerometers, gyroscopes are also under the pressure of multi-axis on-chip cointegration. Different approaches exist, starting from the parallel implementation of three one-axis gyroscopes to synchronized driving of multi-body systems up to one-mass structures movable in all three DOF. Until now only the first two approaches have been commercially successful.

An example of a three-axis gyroscope with synchronized driving modes according to [31] is given in Figure 32 ([32]). The gyro consists of eight radially and synchronously driven segments angularly separated by 45°. Four segments that are angularly spaced apart by 90° are not carried by the central suspension but suspended directly at the substrate. The high \( z \)-stiffness of the suspension neutralizes out-of-plane Coriolis forces. Two opposite segments out of the other four plates are linked by the Cardan suspension in two pairs, any of which may tilt about the \( y \)- or \( x \)-axis in response to the corresponding components \( \Omega_x \) and \( \Omega_y \). Electrodes placed underneath allow independent differential capacitive measurement for any of the in-plane rate signals. The four \( \Omega_z \)-sensitive frames nest sub-frames that can deflect orthogonally to the radial.
movement. The sense boxes within the sub-frames capture the Coriolis deflections stemming from the $\Omega_z$-component.

### 5.3. Fluidic MEMS

Fluidic MEMS are aimed at measuring or handling fluid flows. They can be roughly divided in

- Flow sensors and
- Fluidic actuators.

Most flow sensors use thermal processes in gaseous and liquid flows. A local heating causes flow-dependent heat loss that can be estimated by measuring the necessary power to keep the temperature of the heater constant or by controlling the temperature for constant heating power (anemometers or heat loss sensors). The local heating causes a heat transport depending on the flow rate that can be also measured by placing at least two temperature sensors on both sides of the heater (calorimetric sensor). The upstream flow cools one sensor while the downstream flow is heated transporting the heat from the heater to the sensor. Calorimetric sensors and anemometers are the most often used flow sensors and are produced in high quantities.

The response time and sensitivity of all thermal flow sensors depend on their heat capacitance. Therefore, low masses and good thermal isolation of heaters and thermal transducers are mandatory to avoid heat leakage. The most frequently used constructions are based on placing heater and sensor on free-standing cantilever beams or membranes immersed into the flow.

A huge variety of thermal flow sensor designs exist, some of them are presented in [10].

Fluidic actuators play a crucial role in designing BioMEMS, especially for miniaturized total analysis systems ($\mu$TAS) in medicine whose goal is to transfer the total biochemical analysis from the laboratory’s desktop to a hand-held equipment.

Design of fluidic MEMS has to take into account the considerably different behavior of microfluidics from macroscopic fluidic flows.

#### 5.3.1. Microfluidic Properties

Microfluids are fluids within microchannels and microchambers, or free and surface-bounded microdroplets. In general, in no other MEMS area are the becoming dominant surface effects so obvious as in microfluidics.

The flow in microchannels is laminar. If two fluids are fed into a microchannel, say, one from the top and the other from the bottom, they do not mix efficiently, because of the strong laminarity of the flow. Only long lasting diffusion over long channels can lead to sufficient mixing. The mixing speed can be increased by inserting sharp bends into the channel in order to provoke turbulence. Therefore, active mixers should operate with large flow velocities.
Surface tension plays an important role in microfluidics. If a liquid droplet is placed on a solid surface two surface areas exist: droplet–surface and droplet–environment (e.g., air). The differing free energy levels at both surfaces lead to a strong adhesion of the fluid to the solid surface with a certain contact angle (see Figure 33(a)). This angle can be changed by applying an electric field. If embedded into an optical fiber the corresponding droplet deformation can be used for the control of optical properties.

Electrowetting is an effect that is more and more often used. It is based on the fact that the contact angle between droplet and solid surface changes if an electrical field is applied. In Figure 33(b) the application to digital droplet transport is illustrated (see, e.g., [48]). The droplet is embedded between a top electrode, which is covered by a conducting hydrophobic layer, and an array of lower electrodes, which are electrically isolated from the droplet in order to avoid electrolytic processes. If the second electrode is switched on, the right contact angle decreases and the droplet deformation generates a force and a corresponding droplet shift. Switching on the next electrode a subsequent movement follows, etc. The hydrophobic layer is inserted to improve the movability of the droplet.

Surface tension can also be controlled by using different electrolytic effects. Electrolytes are solutions of ionic species. Electrical fields can impact their fluidic properties. Electro-osmotic flows are generated by electrical fields applied along a channel. The fluid has some free net charges within a region with small distance to the channel’s surface. The free charges are the result of an ionic double layer that emerges at the surface and leave the surface with some net charge. Aside from some small regions close to the channel’s wall the electrically generated flow is uniform and well suited for fluidic transport processes in chemical analysis systems.

Another effect is electrophoresis. If into a background electrolyte, subject to an osmotic flow, minute additives of other ionic species are mixed in, they drift in the electric field \( E \) with their electrophoretic mobility \( \mu_{\text{ep}} = v_{\text{ep}} / E \) (\( v_{\text{ep}} \)–velocity, \( E \)–applied electric field). The different flow velocities allow us to separate the additive, which is, for instance, a protein segment or an amino acid. Separation columns and well controlled injection and detection cycles are needed in order to analyze the separated additive.

![Figure 33. Surface tension and application towards droplet transport](image-url)

5.3.2. Fluidic Actuators
One of the oldest MEMS actuators is the inkjet print channel – the basis for building inkjet print heads consisting of an array of synchronously controlled channels. Today, most common inkjet technologies are the thermal and piezoelectric drop-on-demand ink-jet methods. A thermal inkjet as shown in a simplified manner in Figure 34(a) consists of an ink chamber with heater and output nozzle. A short pulse of less than a few microseconds heats the ink up above the critical temperature for bubble nucleation. The water vapor bubble instantaneously expands to force the ink out of the nozzle, the ink droplet breaks off and excels toward the paper, and the bubble starts to collapse. After ink refill the process starts again.

As an alternatively to the thermopneumatic approach an electrical pulse on a piezoelectric disc can contract a membrane and reduce the chambers volume. A droplet will be generated.

The inkjet channel can be seen as a kind of micropump. In general, valves and pumps are the basic elements of fluid actuators. Micropumps can be divided into mechanical and non-mechanical devices. Actuation mechanisms and valve membranes or flaps are the building blocks of mechanical pumps. They can be driven by electrostatic, piezoelectric, electromagnetic, thermopneumatic and other forces. Non-mechanical pumps exploit electro-hydrodynamic, electro-osmotic, electrochemical or ultrasonic flow generation processes.

In Figure 34(b) the typical ingredients of a micromachined mechanical pump are shown. A pump chamber is formed by a wafer-bonded sandwich usually made from etched silicon or silicon-glass wafers. A diaphragm closes one side of the chamber; the opposite wall consists of an inlet and an outlet valve. The valves can be passive as in the figure or active. Passive valves open and close according to the pressure difference on both sides of the valve. Active valves are driven by appropriate actuators and usually have a lower leakage than passive valves. Piezoelectric, thermopneumatic and electrostatic (capacitive) drivers are the most common.

Such reciprocating mechanical pumps are used in drug delivery systems, in cooling systems for microelectronic devices and in miniature systems for chemical and biological analysis (μTAS).
Electroosmotic and electrowetting flow generators are non-mechanical or dynamic micropumps. Electrohydrodynamic and magnetohydrodynamic pumps have also been developed.

Fluidic micro-biological reactors are basic elements of BioMEMS. Usually they are based on cautiously controlled thermal chambers or channels with attached tubing for sample and reagent insertion and removal. Due to the low temperature capacitance and good thermal isolation of micro-chambers short temperature transfer intervals and, hence, short overall reaction times can be achieved. In particular, the use of the polymerase chain reaction (PCR) to generate thousands to millions of copies of a particular DNA sequence (DNA amplification) is one of the most promising representatives for ‘lab-on-a-chip’ applications with high volume potential.

5.4. MOEMS

Micro-opto-electromechanical systems (MOEMS) can be viewed as the combination of MEMS technologies and micro-optics. MOEMS provide a large variety of tools for visualization, optical communication and optical analysis. Fresnel- and spherical lenses, capacitively driven optical attenuators and waveguides can be fabricated using MEMS technologies. New opportunities have been opened up using arrays of micro-mirrors, diffraction gratings and Fabry-Perot resonators for projection displays and optical switches. There exist many other building blocks for MOEMS (see, e.g., [56] and [57]). To those belong flat silica-on-silicon and polymeric single-mode and multi-mode interference waveguides, tunable waveguides and vertical-cavity surface-emitting lasers, different branching devices, microbolometers and others. They are examples for the merger of MEMS technologies and microoptics.

In what follows the specific properties of micro-optical devices and some selected applications are described.

First, it has to be noted that the dimensions of micro-opto-electromechanical structures are in the same order of magnitude as the wavelength of visible and infrared light. Furthermore, they match with the transverse dimensions of optical fiber cores supporting a smooth transfer to optical fiber networks. The similarity of wavelengths and geometric dimensions invalidates the laws of geometrical optics. Therefore, the application of ray optics must be handled with care. Diffraction and interference effects play a dominant role.

Diffraction effects such as optical beam forming are usually modeled by Gaussian beam optics and allow to determine the necessary dimensions of a light source (e.g., a mirror) to get a required beamwidth at a certain distance (see, e.g., [67]).

Interference effects are used to separate different wavelengths in space by diffraction gratings or Fabry-Perot resonators. In particular, diffraction gratings are predestined to be fabricated in microfabrication technologies. Similarly reflective elements such as mirrors benefit from the optical quality of micromachined surfaces.
Fabry-Perot resonators are based on the interference of multiple reflected wavefronts. Two partially reflective surfaces encase a material with refraction index $n$. The light enters with small inclination angle so that in rough approximation the light path between the plates equals their geometric distance $d$. Due to multiple inner reflections an escaping wavefront interferes with others which have passed an additional optical path of $= m \cdot n \cdot d$ ($m = 1, 2...$). Therefore, for a given wavelength $\lambda$ maximal transmission takes place if

$$d = \frac{m \cdot \lambda}{2n}$$

(8)

Since the maximal transmission depends on the distance between the plates it can easily be controlled in MEMS, for instance by capacitive actuation of one of the active surfaces. Therefore, Fabry-Perot interferometers are well suited for designing wavelength dependent optical filters. They are used intensely for optical demultiplexers for wavelength-division multiplexing systems.

However, the presently dominant application of Fabry-Perot resonators seems to be Qualcomm’s interferometric modulator display (IMOD), where each pixel of an array may be switched on by actuating the partially reflective front surface of a Fabry-Perot resonator. The deflection of the front membrane shifts the constructive interference from visible wavelengths to invisible short wavelengths.

The outstanding role of micro-mirrors for successful high-volume applications makes it meaningful to consider them in more detail.

Movable micro-mirrors redirect optical beams. Usually an on-chip micro-mirror is arranged parallel to the substrate and suspended by an in-plane torsional hinge. The deflection angle is limited by the gap to the substrate. In the case of capacitive actuation the pull-in effect further reduces the inclination to less than one third of the gap.

The main applications of micro-mirrors are projection displays and optical switches. The most popular representative of projection displays is Texas Instruments DMD (digital micro-mirror device). It consists of a matrix-like array with more than one million singular elements called pixels.

They are operating in parallel projecting white light or switched colored beams onto the screen or onto the focal plane of the optical projector. Systems with three parallel chips for each of the colors also exist. The image-controlled transmission of each individual micro-mirror pixel determines the grey-level or the color content of that pixel on the screen. Grey level control is realized by fast switching of the micro-mirrors, thus transforming the desired intensity into a pulse-modulated sequence of light.
Figure 35 schematically shows a pixel design. The left drawing represents the overall view; the next three – the top, the middle and the bottom level of the structure. Each pixel consists of control electronics (not shown) implemented on the substrate carrier. The aluminum mirror is mounted via a central post on the mirror support and, therefore, is not stressed and nearly ideally plane. The mirror support is suspended by two torsional springs and electrically grounded. On both sides there are landing pads, which also are at ground potential. The two underlying butterfly-like electrodes alternately attract one of the half-areas of the support causing a fast tilt until the upper mirror tip contacts the landing pad. Since both are at ground potential, no electrical attraction occurs. The applied voltages are higher than the pull-in voltage, however stiction is avoided by the landing pads that prevent the contact between support plate and electrodes. Large tilt angles of much above the one/third gap limitation can be realized. In one of the mirror states the light is projected towards the screen resulting in a bright pixel. In the second state the light is directed aside which causes the pixel to appear dark. The angle between two states is approximately 20°; the switching frequency – around 1 kHz.

A grating light valve (GLV) is even faster in switching light than DMD-mirrors. GLV arrays are composed of one to two thousand rows of linear pixel arrays with more than a thousand pixels per row. The technique was developed and commercialized by Silicon Light Machines. A GLV pixel from a GLV row consists of a small diffraction grating made from four or six double clamped conducting ribbon-beams – usually silicon nitride – which are covered with a highly reflective aluminum top layer. The principle of a GLV-pixel is illustrated in Figure 36. The beams are suspended over an air gap. Underlying tungsten electrodes deposited on insulating silicon oxide attract the long central part of two (or three) interleaving beams (active ribbons are interlaced with static ribbons) creating a phase difference of approximately π with their neighbors. Therefore, the pixel state is switched from reflection, which takes place in un-deflected state, to strong diffraction. Hence, beam deflection must be approximately one quarter of the wavelength. Deflection switching takes about 20 nanoseconds. The absence of any physical contact between moving elements reduces wear and makes the lifetime of the GLV as long as 15 years without stopping.
Micro-mirror arrays have been considered as possible central devices for optical cross-connect switches. MEMS based ‘all optical’ cross-connect switches avoid optical-electrical conversion. They are based on arrays of mirrors as illustrated in Figure 37. For the connection of $N$ input and output channels $N^2$ mirrors are required.

Figure 36. Pixel of a Grating light valve

Figure 37. Mirror array for optical cross-connect switch
The mirrors must be switched into the light path or away from it. In the figure two mirrors are active: the connection 1 to 4 and the connection 4 to 2.

The mirror-pixels of 3D switching arrays redirect an incoming beam into any of the desired directions. Therefore, mirrors that tilt about two axes are needed. Each individual mirror is illuminated by its assigned input channel and redirects the beam to one of the required output channels. Only $N$ switches are needed for an $N$ to $N$ connection.

In both cases the switching speed must be very high in order to reroute short data packets. This and the difficulties of large mirror arrays have lead to a decreasing interest in optical matrix switches.

5.5. RF-MEMS

RF-MEMS substitute previous external components for Radio-Frequency-communication IC’s like inductors, varactors, RF-switches, resonators, filters and phase shifters, that in MOS-technologies could be integrated on-chip only with insufficient performance.

Traditional RF-inductors suffer from high ohmic losses (small Q-factor) and large parasitic couplings to the substrate. For instance, inductors have been developed in advanced CMOS technologies using up to nine metal layers. Spiral solenoids have also been presented (see, e.g., [28]). However, only moderate Q-factors in the range from five to fifteen have been achieved. In contrast, micromachined inductors are positioned over thick dielectric layers or even cavities in order to reduce the capacitive coupling to substrate – see Figure 38. The ohmic losses are decreased by using gold or similar metals with low specific resistance. High-quality inductors result, which, however, find only limited application due to the rather high additional cost.

![Figure 38. Spiral inductor](image)
A similar situation takes place for varactors, which in CMOS are based on diode- or transistor caps. Micromachined varactors are usually based on capacitors with one movable electrode. The pull-in effect limits the capacitance changes to 30%. Larger tuning ranges can be achieved by mechanical amplification of the relative displacement, as illustrated in Figure 39 (see, e.g., [18]). The set electrodes deflect the movable plate by up to 30% of the actuation distance $D_{\text{act}}$; the varactor gap $D_{\text{var}}$ may change, however, by nearly up to 100%. A wide tuning range is achieved.
The most frequently used RF-MEMS-devices are RF-switches, because they can substitute the expensive and bulky external relays. For very high frequencies capacitive switches are well suited. The principle is shown in Figure 40. The switch is a metal-gap-dielectric-metal structure. The upper metal plate forms a bridge. If the bridge is not actuated it is electrically decoupled from the transmission line. An external voltage at the actuating electrodes forces the upper plate to collapse and to contact the dielectric. Therefore, the coupling capacitance increases by a factor up to some hundred. Switching frequencies are relatively low, because a mechanical transfer process must be forced. Typical switching frequencies are from dozens to some hundred kHz. For high-quality switches in the lower GHz range quite large capacitances are required, which often are realized by multiple switches. To avoid the accumulation of charges within the dielectric layer, which can lead to stiction, the hold voltage after the switch transfer process is reduced as much as needed for a reliable contact.

Ohmic switches are mostly based on capacitively actuated cantilever beams with ohmic contacts at the tip. A reliable contact requires a certain contact force. Hence, multimillion switching cycles deteriorate the metal-metal contact interfaces, thus limiting lifetime. The lifetime can be increased if a current flow during the switching process is avoided (cold switching).

RF-MEMS-resonators are used as filters and, increasingly, as clocks. Mechanical resonators can be based on clamped-clamped beams, as presented in Section 5.2.1, on centrally anchored beams with longitudinal mode, as shown in Figure 41, on diaphragms, on acoustic wave resonators, etc. The most often used resonators are longitudinal-mode beams with piezoelectric actuation and sensing. The axial forces excite longitudinal oscillations. If the oscillation nodes are positioned in the middle of the beam where the anchors are attached, the anchor losses are eliminated, and high Q-factors are achievable.
Besides mechanical resonators, CMOS-compatible electromagnetic waveguide-, strip-line- and cavity-resonators have been improved using typical micromachining technologies (see, e.g., [61]).

**Glossary**

- **AC**: Alternating current
- **Adhesion**: The tendency of dissimilar particles and/or surfaces to agglutinate to one another
- **AFM**: Atomic force microscope
- **Anisotropic Magnetoresistance (AMR)**: Dependence of electrical resistance of a material on the angle between the direction of electric current and orientation of an applied magnetic field.
- **Application Specific Integrated Circuit (ASIC)**: Integrated circuit which is designed according to some customer specific application requirements
- **Ashing**: Removal of the photoresist from an etched wafer
- **Bulk Micromachining (BMM)**: Creation of MEMS structures out of bulk material
- **CAGR**: Compound annual growth rate
- **CCD**: Charge coupled device – transports charges within the device; used mainly within digital image sensor arrays
- **CMOS**: Complementary metal oxide semiconductor – the main IC production technology; uses complementary pairs of p-type and n-type metal oxide semiconductor field effect transistors (MOSFETs) for logic functions.
- **Chemical Vapor Deposition (CVD)**: One or more volatile precursors react with or are decomposed on the substrate surface producing this way the desired deposit
- **Curing**: Hardening of a polymer material by cross-linking of polymer chains by heat, ultraviolet radiation or other means
- **DC**: Direct current
- **Deep reactive ion etching (DRIE)**: A highly anisotropic etch process which is used to create deep trenches or holes in wafers. It is a basic MEMS process especially for BMM
- **DETF**: Double-ended tuning fork – special design of a force-sensitive double-beam resonator
- **DLP**: Digital light processing – a digital control technique for optical beams
- **DMD**: Digital micro-mirror device – the basic device of Texas Instruments for building projection displays
- **DNA**: Deoxyribonucleic acid – a nucleic acid that contains the genetic information necessary for the development and functioning of living organisms
- **DOF**: Degree of freedom
Doping: Introduction of impurities into an extremely pure semiconductor in order to change its electrical properties. Boron doping in Si creates a p-type semiconductor (electron flow), Phosphorus – an n-type semiconductor (flow of holes)

E-beam: Electronic beam – the E beam lithography is based on the emission of a steered beam of electrons which creates a pattern of exposed photoresist

E-modulus: Elastic modulus, modulus of elasticity – the ratio of small stress changes to the corresponding strain changes in the elastic deformation region

ESP: Electronic stabilization system – a system of sensors, control algorithms and actuators in cars which potentially improves the safety of a vehicle by detecting and minimizing skids

First Level Packaging (FLP): Final packaging of a MEMS device in order to protect the MEMS device together with its signal processing part

GMR: Giant magnetoresistance – a quantum mechanical magnetoresistance effect in thin stacked layers composed of alternating ferromagnetic and non-magnetic layers

Grating Light Valve (GLV): Basic element of the company Silicon Light Machines for light switching in projection displays based on diffraction gratings

IC: Integrated circuit

Hall sensor: A magnetic transducer based on the Hall Effect

IMOD: Interferometric modulator display – projection display, which is based on interferometric color selection and produced by the company Qualcomm

IR: Infrared light

Liquid Crystal Polymer (LCP): Special class of polymers, which – similar to regular solid crystals – are forming regions of highly ordered structures while in the liquid phase

LED: Light emitting diode

Lorentz force: The force on a point charge due to an electromagnetic field

Magnetostriction: The change of shape or dimensions of ferromagnetic materials during their magnetization

MEMS: Micro electro-mechanical system

μTAS: Miniaturized total analysis system – an automatized chemical or biomedical analysis system shrunk to chip dimensions (lab-on-a-chip)

MOEMS: Micro opto-electro-mechanical system

MOS: Metal oxide semiconductor – field-effect transistors with a metal gate electrode placed on top of an oxide insulator. The insulator separates the gate from the underlying
Parylene polymer : Chemical vapor deposited poly(p-xylylene) polymers used as moisture and dielectric barriers
PCB : Printed circuit board
PCR : Polymerase chain reaction – a method to amplify copies of a piece of DNA generating many thousands of copies of a particular DNA sequence.
PVD : Physical vapor deposition – vacuum deposition of thin films by condensation of a vaporized form of the desired material
Poisson’s ratio : The ratio of transverse strain to axial strain in the case of an applied axial load
PVDF : Polyvinilidene fluoride – a thermoplastic fluoropolymer with exceptionally strong piezoelectricity of poled thin films
PZT : Lead zirconate titanate – a ceramic perovskite material (a calcium titanium oxide mineral) with strong piezoelectric effect.
RIE : Reactive ion etching – high-energy ions from a plasma, which is generated in vacuum by an electromagnetic field, attack the surface. The reaction products are removed from the surface.
RF : Radio frequency
Si : Silicon
SMM : Surface micromachining – creation of movable MEMS structures from layers on the surface of a wafer
SNR : Signal-to-noise ratio – determines the degree of signal disturbances and with it the achievable signal resolution
Sigma-Delta-Converter : Transforms high-resolution ’slow’ (analog) signals into ’fast’ low resolution digital signals without significant loss of information
SOI : Silicon on insulator – a silicon layer is separated from the (silicon) substrate by an insulator (usually silicon oxide). Initially developed to reduce the impact of parasitic capacitances of active devices.
Sol-gel deposition : A wet-chemical technique to deposit materials starting from a colloidal solution (sol) that acts as the precursor for a gel of discrete particles or network polymers
Spin casting : Centrifugal rubber mold casting
Stiction : Adherence of two surfaces which have come in close proximity. May be caused by electrostatic, Van der Waals, hydrogen bond and many other forces in the microscale region.
TMR : Tunnel magnetoresistance – a magnetoresistive effect in structures consisting of two ferromagnets separated by a
thin insulator (magnetic tunnel junction)

**Transducer**
- Converts signals from one energy domain to another domain

**Varactor**
- Voltage-controlled capacitance

**VCSEL**
- Vertical-cavity surface emitting laser – semiconductor laser diode with laser beam emission perpendicular to the top surface

**Young’s modulus**
- Elastic modulus for tensile stress and strain

**Zero-level packaging**
- Encapsulation of a MEMS element in order to create an appropriate working environment and/or to protect the MEMS element during die separation and first-level packaging

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Biographical Sketch

Volker Kempe has a unique double background in both fundamental science (physics) and engineering (communication technology). From 1957 – 1963 he studied Physics and Communication Science at the Moscow Energetic Institute, received his PhD degree (Dr.-Ing.) in 1968 with Summa Cum Laude and in 1976 his PhD degree (Dr.sc.nat.) for his work on the theory of stochastic systems (on which he wrote two books). In 1978 he was appointed Professor of Information and Control Theory by the Academy of Sciences in Berlin, and became a full Member in 1986; and in 1988 was elected full Member of the International Academy of Astronautics. His research interests include Stochastic Systems, Conditional Markov Processes, Optimal Estimation Theory and MEMS. He led the development of Infrared Fourier Interferometers for remote sensing of the earth's atmosphere by satellites used later, among other things, for the exploration of the atmosphere of the planet Venus. Accompanying a lifelong investment into research are 40 years of experience in the management of research and development, both in academia and industry. From 1977 to 1990 Volker Kempe headed the Institute of Cybernetics and Information Processes of the Academy of Sciences in Berlin and set up an internationally strong research institute in informatics, artificial intelligence and automation, with a leading role in selected areas such as image processing, and expanded the institute from less than 200 to over 600 employees. He worked on topics including powerful image processing systems and established and organized broad research activities in special directions of control and automation, in robotics, and in foundations of microelectronic design. In 1990 he moved to the microelectronic industry and led the Engineering Department of Austria Mikro Systems and later its Strategic Product Development. In 2003 he co-founded SensorDynamics AG, a fast-growing semi-fabless semiconductor company that focuses on innovative sensor solutions, of which he has been the VP of R&D. He has authored over 100 papers and more than 20 patents, four books and five scientific anthologies, and edited four journals and book series. He has been in the program committee of several major international conferences, including ESSCIRC and DTIP.

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