Spotlights on Recent Developments in Microsystem Technology

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Abstract

Microsystem technology introduces a new way of integration of sensors, actuators, and information processing components resulting in flexible, adaptive, and intelligent systems similar to those created by nature. This paper attempts to give a general idea of what is feasible with this technology. After a short introduction the key technologies for the fabrication of microsystems are described and illustrated by several examples of present-day applications.

1 Introduction

Since 1960 the complexity and performance of microelectronic devices have been increased by many orders of magnitude, whereas size, power consumption, and price have been reduced significantly. This development has led to numerous new applications of microelectronics.

Microelectronic systems are connected to the real world by means of sensors and actuators. Today the majority of transducers is still fabricated by conventional techniques of precision mechanics. This limits further system integration and penetration of microelectronics into new products. As a consequence there is a large demand for sensors and actuators which are compatible to integrated circuits with respect to driving voltages, power consumption, size, weight, complexity, and price, and which can be integrated with microelectronic functions into one device.

The desired compatibility of transducers and microelectronics can be achieved by the new concept "micromachining", which stands for the exploitation of the highly developed batch processing techniques of integrated circuits to the fabrication of sensors and actuators with very small dimensions [1]. Consequently, the creation of complete miniaturized systems is expected to be the next step of integration after the integrated circuit.

The enormous potential of microsystems results from the following particular features of this new technology:

- Materials:
  - Utilization of materials and sophisticated processes already developed in semiconductor technology resulting in low production costs.
  - Use of new materials, for example biological receptors used in biosensors or shape memory alloys and ferroelectric compounds applied in microactuators.
- Miniaturization:
  - Extremely small size and weight as well as low power consumption, which are essential for stand-alone, portable or implantable systems.
  - Fast mechanical and thermal response times and low interference with the measurement environment.
- System integration:
  - Due to the large scale of integration complex and multifunctional systems can be realized.
  - An increase in reliability can be expected due to the reduced number of external connections and to new concepts for control architectures and signal processing.

2 Key technologies for the fabrication of microsystems

One of the main differences in manufacturing integrated circuits or micromachined sensors and actuators is the fact that integrated circuit technology usually employs planar processes only, whereas in micromachining three-dimensional and movable elements with functions different from those of integrated circuits have to be fabricated. For this purpose special processes and materials have to be added to the technological basis borrowed from microelectronics.

2.1 Bulk micromachining

Bulk micromachining exploits chemical anisotropic etching with alkaline solutions as well as deep dry etching for selective removal of material to fabricate three-dimensional microstructures mainly of silicon.

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Basic structures that can be fabricated by anisotropic etching of single crystal silicon are pits, grooves, membranes, cantilevers and bridge-like structures [2]. These structures are the starting points for the fabrication of miniaturized sensors and actuators. A membrane (fig. 1), for example, can be used as the movable part of a valve, cantilevers may act as spring-mass systems in accelerometers.

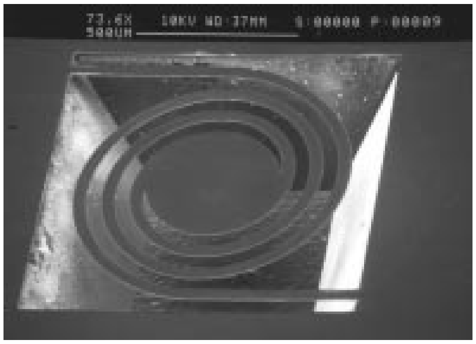


Fig. 1. SEM micrograph of a silicon membrane suspended over an etch pit

The shape of the microstructures resulting from anisotropic etching of silicon depends strongly on the crystallographic orientation of the substrate. This limitation can be overcome by using a technique based on the local destruction of etch limiting crystal planes by laser melting and subsequent anisotropic etching of the molten zones [3]. Using this method vertical-walled shafts and microchannels with high aspect ratio can be fabricated.

In dry etching processes a plasma instead of a liquid is used as the source of chemical reagents. Dry etching is widely applied in integrated circuit technology. The main advantage when used in micromachining is the fact, that the shape of the resulting microstructures is not dictated by the crystallographic orientation of the substrate as in chemical etching.

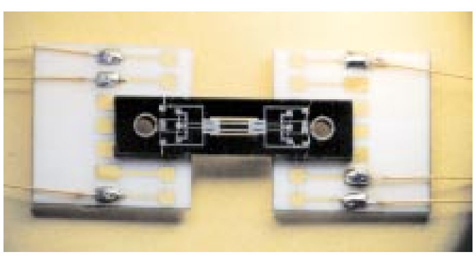


Fig. 2. Micrograph of a resonant triple-beam force sensor [4]

Deep dry etching processes with high etch rates, high anisotropy, and high selectivity, which allow the fabrication of three-dimensional microstructures, are presently under development at several laboratories. For deep etching of silicon a high-rate plasma process using a mixture of sulfur hexafluoride and a chlorine containing gas shows an almost perfect anisotropy. Etch depths larger than 50 µm could be achieved with a photoresist mask. This process has been used, for example, as a final processing step of the piezoelectrically driven resonant triple beam force sensor of fig. 2 [4]. The piezoelectric drive has been realized by zinc oxide layers deposited by reactive sputtering. The silicon substrate is anisotropically etched with potassium hydroxide solution from the backside down to a membrane of 20 µm thickness. Subsequently the beams are defined by through-etching of the membrane from the front side using the plasma process. The measured force sensitivity of this sensor is about 8 kHz/N.

2.2 Surface micromachining

In surface micromachining the mechanical devices are machined in thin layers that have been deposited on the surface of the substrate. This technology is based on the sacrificial layer method which takes advantage of the selectivity of isotropic etchants to different materials.

One starts from sandwich layers, for example of silicon dioxide and polycrystalline silicon, deposited on standard silicon substrates. The poly-silicon is used as the mechanical material and is structured by lithography and etching. The sacrificial silicon dioxide layer is etched away completely with a high selective hydrogen fluoride etchant leaving free standing poly-silicon structures or releasing movable parts. This technique has been used to fabricate the sensing element of the monolithic accelerometer of fig. 3 [5]. The microsensor consists of a seismic mass of about 1 mm^2 in the form of the big letter "H". The mass is anchored to the substrate by the long, thin arms of the "H". Acceleration exerts a force on the mass, which moves and displaces tiny interdigitated capacitor plates. This displacement causes a change in capacitance, which is detected and processed into a high-level voltage output

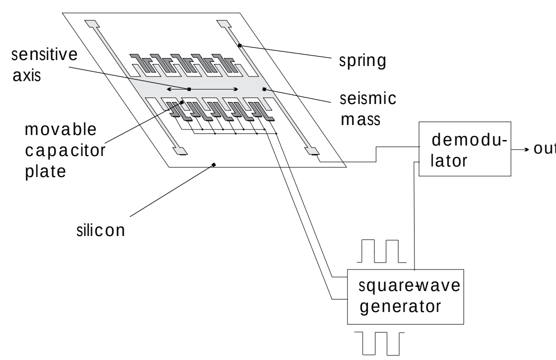


Fig. 3. Schematic drawing of a surface-micromachined accelerometer

using a monolithically integrated electronic circuit. The sensitivity is about 20 mV/g at a measuring range of 50 g.

In order to overcome problems due to sticking effects and to constraints in structure height some recent developments [6] use plasma release techniques instead of wet chemical etching for the fabrication of movable microstructures.

2.3 Quartz micromachining

The exceptionally high elasticity accompanied by practically negligible hysteresis and the high chemical resistivity make single-crystal quartz a most suitable material for microresonators with long-term stability. The intrinsic piezoelectric effect can easily be used to excite stable mechanical resonance vibrations with a high Q value.

Quartz microresonators which are usually applied as resonant microsensors can be batch-fabricated using photolithography and anisotropic chemical etching. The commonly used fabrication process starts with the deposition of a Cr/Au layer by r.f. sputtering onto the quartz blank serving as both masking layer during quartz etching and metallization layer. Photolithography is used to define the resonator geometry and after opening the Cr/Au masking layer the electrode areas are defined in a second lithographic step. Then the quartz is chemically milled in an aqueous solution of NH_4F@HF at about 80 EC. In the next process step the Cr/Au layer is etched in order to pattern the electrode areas. Alternatively, patterning of the electrodes can be performed simultaneously on both sides of the quartz substrate by a Nd:YAG laser beam [7]. In this case the second lithographic step does not apply.

2.4 The LIGA process

Micromechanical structures of metals and plastics with extreme aspect ratios can be fabricated by deep X-ray lithography. Polymethyl-methacrylate type resist up to 600 µm thickness is irradiated by synchrotron radiation using special masks. The developed resist structure is filled up by metal deposited by electroforming. If parts of the microstructure shall be movable they have to be applied on a sacrificial layer which is etched selectively after electroforming. The metallic microstructures can also be used as a mould insert for the fabrication of plastic replicas. Using this so-called LIGA technique [8] the electrostatic micromotor shown in fig. 4 has been fabricated [9]. The rotor radius is 700 µm, the axle radius 400 µm, and the height 120 µm. This motor has been operated up to 3600 revolutions per minute.

A low-cost alternative to the LIGA process uses photosensitive polyimide as a resist material, ordinary masks and ultraviolet light exposure [10]. Although the resolution of this process is inferior to the LIGA process it has

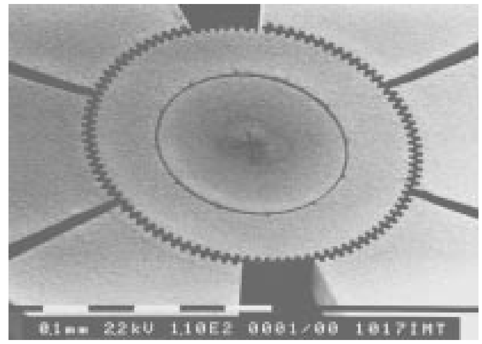


Fig. 4. SEM micrograph of an electro - statically driven nickel micromotor
(courtesy of W. Menz, FZK, Karlsruhe)

the advantage that it is simple and can be carried out using commercially available equipment.

2.5 Laser micromachining and microcutting

The technologies based on integrated circuit processing techniques are complemented by laser micromachining and microcutting. These techniques allow to fabricate a large variety of three-dimensional microstructures. Fig. 5 demonstrates, for example, how fine silicon can be structured using microcutting techniques.

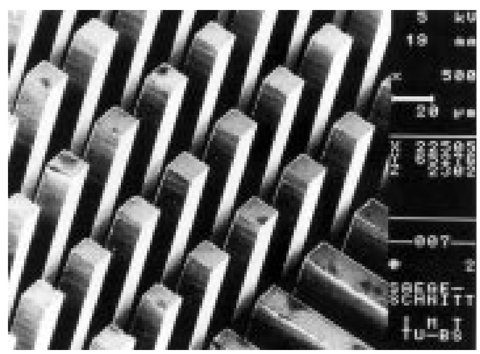


Fig. 5. SEM micrograph of silicon pins (15 µm x 15 µm x 400 µm) fabricated by microcutting

3 Examples of present-day microsystems

Today, merging micromachined sensors and actuators with integrated circuits as single-chip or hybrid microsystems has been demonstrated at the laboratory as well as at the industrial level. Some examples shall illustrate the state of the art.

3.1 Automotive applications

Due to the large number of units needed automotive applications are expected to be one of the biggest market segment of microsystem technology. The available space in cars decreases, whereas the number of additional functions is growing rapidly because of more stringent safety, environmental and economic demands. To overcome this difficulty microsystem technology has to be applied instead of the conventional techniques [11]. Therefore, the first silicon chips, in which microelectronic and micromachined functions have been integrated monolithically, have been developed for automotive applications.

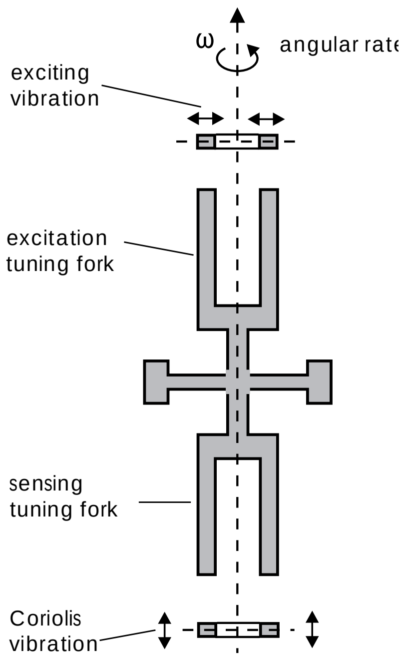


Fig. 6. Schematic drawing of a quartz micromechanical gyroscope

An example is the monolithic accelerometer of fig. 3, which has been developed for airbag release and other automotive applications. Another key component is a micromechanical gyroscope needed in active chassis development as well as for inertial navigation systems. Fig. 6 shows schematically a gyroscope that measures the angular rate by means of a vibrating quartz tuning fork [12]. Due to the Coriolis force a rotation of the sensor about its longitudinal axis causes a vibration of the sensing tuning fork with an amplitude proportional to the angular rate. The resolution is 0.002 °/s at a measuring range of 100 °/s. Micromechanical gyroscopes have also been fabricated by silicon micromachining [13].

3.2 Resonant microsensors

The rigorous safety demands in automotive applications lead to the development of microsensors with integrated self-test. The technology used to integrate the self-test has to be compatible with the sensor fabrication process. Fig. 7 shows the concept of a piezoresistive pressure sensor with self-test that fulfils this condition [14]. During a self-test cycle piezoelectric thin film AlN is used to excite vibrations of the sensor membrane, which are detected by the sensing resistors.

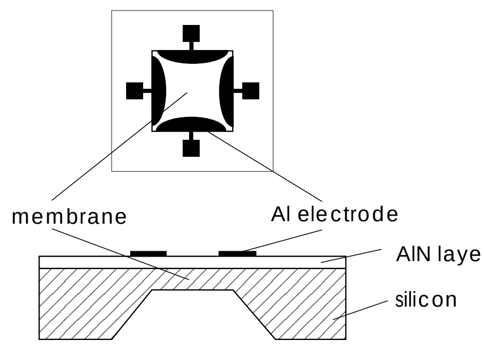


Fig. 7. Concept of a pressure sensor with self test

Using this technology, also resonant microsensors, which change their output frequency as a function of the quantity to be measured, can be developed [15]. They exhibit a wide field of applications and special benefits like high sensitivity, high resolution, semi-digital output and inherent self-test function.

A resonant silicon force sensor has been described in section 2.1. As an additional example, fig. 8 shows schematically a resonant pressure sensor mounted on a glass plate coated with a patterned conductive ITO layer, which

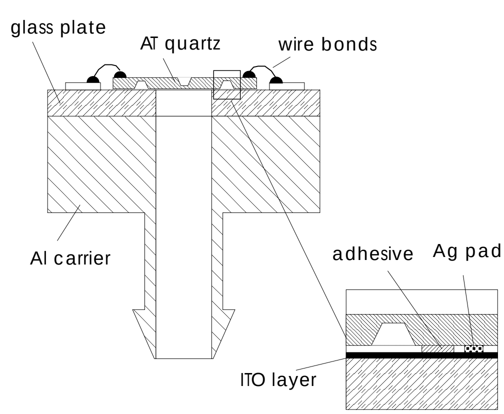


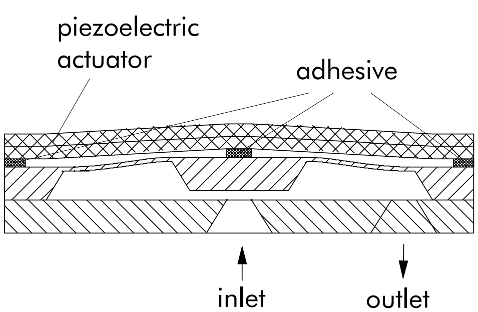
Fig. 8. Schematic drawing of a resonant quartz pressure sensor mounted on an Al carrier

is glued to an Al carrier. The sensor is based on a novel design of a quartz membrane realized with an AT crystal cut [7]. The resonator consists of a full-thickness bossed membrane of about 4 mm diameter, which is monolithically attached to the bulk frame. Applied pressure induces a deformation of the membrane. Extensive finite-element modelling has been carried out to determine the electrode configuration and the shape of the structure for exciting a low-frequency bending mode in the 30-50 kHz range. A very sensitive and stable frequency shift response of about 20 Hz/kPa has been measured.

3.3 Microflow devices and systems

An attractive field of increasing interest is the use of microsystems for chemical analysis and for accurate delivery of small amounts of liquids or gases. There are possible applications in a broad range of the market, for example in industrial process control, biotechnology, environmental control, and medical applications.

A microchromatograph based on a single 2-inch silicon wafer was developed at the Stanford University in 1979 [16]. The system includes a 1.5 m long separation capillary column, a gas control valve, and a thermal conductivity detector. This device opened up a new direction in analytical instruments.



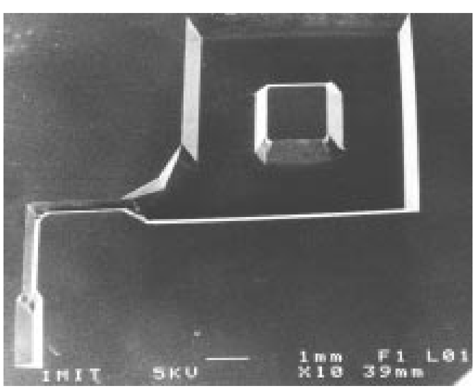


Fig. 9. Basic geometry of a piezoelectrically driven microvalve and SEM micrograph of the bossed silicon membrane [18]

Key components of such systems are miniaturized valves and pumps. Several force transducing principles and designs of such devices have been investigated and realized in the form of prototypes using micromachining methods [17]. An example is a microvalve designed for accurate delivery of liquids in the 10 - 100 µl/min range (fig. 9). The main components are two micromachined silicon parts bonded together and a piezoelectric actuator [18].

3.4 Applications in precision machining

Precision machining is one of the areas in which the application of microsystem technology is of particular interest. Intelligent, resource-saving measurement, control and regulation are becoming increasingly important. An example of an advanced microsystem in this field of application is an intelligent tool for ultra-precision machining of workpieces [19]. The system contains a cutting edge coated with a wear-sensitive layer and a temperature-sensitive bimorph layer. The die holder consists of a large area silicon substrate on which several sensors and actuators are mounted, for example force sensors, a vibration sensor, and an optical position transducer. In addition, there are integrated circuits for signal processing as well as an optical interconnection.

3.5 Light modulators and deflectors

Applications for optical microactuators include displays, printing and optical scanning. Different technologies and actuation principles have been used to fabricate light modulators and deflectors. A device that is nowadays produced in series for commercial application is the digital micromirror device (DMD) shown schematically in fig. 10 [20].

The DMD is a device with 864 x 576 highly reflective mechanical mirrors with an area of 16 x 16 μm^2. Each mirror is suspended by two torsion hinges and built over a pair of address electrodes that are connected to an underlying SRAM cell. The mirrors can be tilted electrostatically plus and minus 10 degrees about their torsional axis.

The DMD is used in conjunction with darkfield optics to provide a highly efficient projection display. Color projection systems can be realized by using a single DMD and a rotating color filter wheel or by illuminating three devices (red, blue, green). Shades of gray or color are accomplished by clocking the mirrors with a type of pulse-width modulation.

The DMD is suitable for all applications that require the modulation or directional switching of light, and it provides a promising alternative to LCD technology in projection television applications.

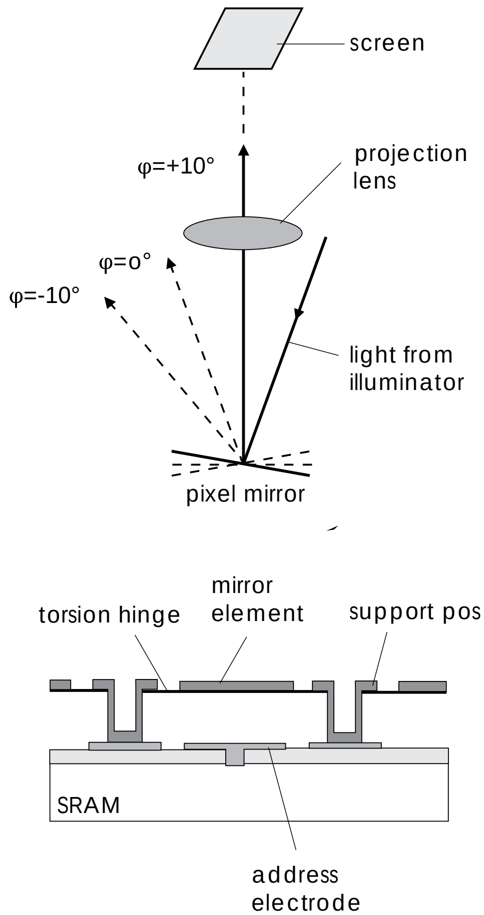


Fig. 10. Schematic drawing of the DMD pixel cell structure and the dark-field projection optics

4 Conclusion

The state of the art of microsystem technology can be summarized as follows. Microsystem technology provides a broad technology basis to fabricate miniaturized complex multifunctional systems in which sensors and actuators are combined with microelectronics. Integrated sensors for the measurement of pressure, acceleration and other variables are already in volume production, and significant progress has been made to develop microactuators like microvalves, pumps and deflectable mirrors using micromachining techniques. Nevertheless microsystem technology is still at its beginning and many challenges have to be solved in the future. But there is no doubt that microsystem technology will trigger a new cycle of innovation and that this will bear the key to future technological progress.

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