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MICRO-STRUCTURED SENSORS AND ACTUATORS: AN OVERVIEW

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Abstract: Micro techniques offer lots of chances for the realisation of new micro sensors and micro actuators. Combinations of microelectronics, micro mechanics and micro optics are used with auxiliary techniques, which can generally be called micro system engineering (MST). The chances lie in new degrees of freedom by utilisation of "micro-physical" effects, in the use of already established production technologies in combination with new materials as well as in the maintenance of the economical microelectronic finishing technique oriented towards mass production ("batch processing"). Promising operational principles as well as substantial development trends are pointed out and discussed on the basis of recently published development results regarding microsensors and micro actuators.

Mikrostrukturirani senzorji in aktuatorji - pregled

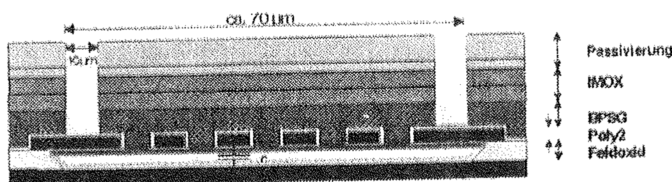
Ključne besede: senzorji mikrostrukturirani, mikrosenzorji, aktivatorji mikrostrukturirani, mikroaktivatorji, MST mikrosistemi, MST inženiring mikrosistemski, MST tehnologije mikrosistemske, mikroelektronika, mikromehanika, mikrooptika, mikrostrukture, pregled razvoja, trendi razvoja, polprevodniki, mikrofizika, MM obdelava najfinejša, miniaturizacija skrajna

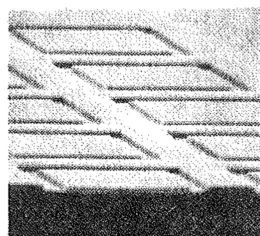
Povzetek: Mikro tehnike ponujajo veliko priložnosti za izvedbo novih mikro senzorjev in mikro aktuatorjev. Kombinacijo mikroelektronike, mikromehanike in mikooptike ob uporabi nekaterih pomožnih tehnik po navadi v splošnem poimenujemo kar mikro sistemski inženiring (MST). Priložnost izrabe leži v novih prostostnih stopnjah pri uporabi "mikro-fizikalnih" efektov, v uporabi že utečenih proizvodnih tehnologij v kombinaciji z novimi materiali, kakor tudi v izrabi ekonomičnih mikroelektronskih tehnologij, ki so usmerjene v masovno proizvodnjo (npr. "šaržna proizvodnja"). Na osnovi pred kratkim objavljenih razvojnih rezultatov v prispevku obravnavam in podajam pregled osnov delovanja in razvojnih smeri tehnologij izdelave mikrosenzorjev in mikroaktuatorjev.

Introduction

Because of its fine structure technology CMOS silicon technology has become a highly developed industrial mass production technology, whereby the structure widths keep being reduced with unchanged speed, while the integration densities are increased accordingly. The main products of this industry are high-complex digital circuits such as microprocessors, memory or telecommunications ICs. Communication and interaction with the usually analog external world requires, however, sensors, actuators or other interface elements at the periphery. As a result of the increasing compact digital electronics the miniaturization of these peripheral elements in the systems becomes more and more significant.

For several years there have been made considerable efforts to use the possibilities and experiences of the fine structure and silicon technology also for micro-structured sensors, actuators or further, up to now not integrable components such as resonators or quartzes for innovative system solutions. In the Federal Republic of Germany e.g. in 1994 the Federal Ministry for science, research and technology promoted a micro system engineering program /1/ and since then approx. 3 billion ATS of public funds have been invested. First industrial applications of MST can be found primarily in automotive electronics (e.g.. acceleration sensors), as well as in the gas analysis by means of IR spectroscopy. Micro system engineering (MST) as generic term of these efforts will therefore become as significant for innovative, economical system solutions in the next years as the CMOS silicon technique for microelectronics. The maturity degree of the MST is, of course, by far smaller, the application possibilities and - principles are clearly more varied, so that the technological beginnings, the used materials and constructions and consequently the entire experimentation field are substantially more varied than in microelectronics. In addition, this situation offers also smaller enterprises the chance to assert themselves in this promising research area.





- Surface Micromachined BICMOS
- Capacitive Sensor Array
- Poly- Si Membrane
- Sens. range: - 1000 mbar

Fig. 1: Micro-structured pressure sensor (source: Siemens)

The article tries to point out the potentials and trends in the area of the micro system engineering. Recent results presented at the end of January '98 at the international conference MEMS '98 (Micro-Electro-Mechanical Systems) in Heidelberg were included. Also present semiconductor technologies must be further developed according to the requirements of the MST elements. Here the following main directions can be recognised:

- Use of new materials (glass, Ni, polymers...)
- Technologies for geometry with extreme height/width conditions..
- New MST specific processes
  - micromachining - processes (surface and bulk -MM)
  - photo lithography (high sharpness depth, 3D-lithography / 2,3 /, x-ray lithography)
  - etching processes for MM (corrosions on the back, structured by structures, free corrode)
  - galvanic figuration
- multi layer connecting procedure (glass, Si) /4, 5/

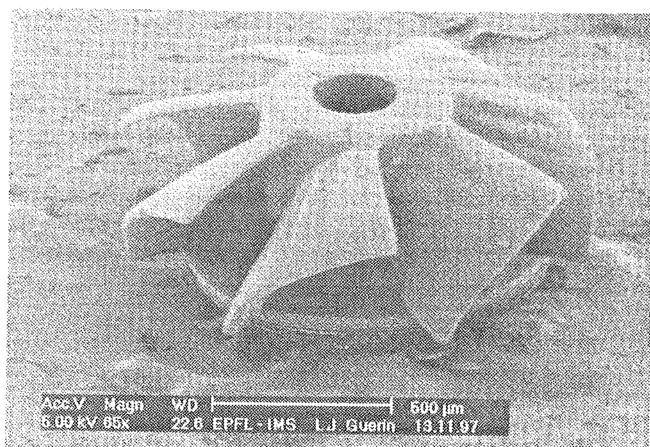


Fig. 2: Microturbine, manufactured with 3D-stereolithography (source: EPFL, Switzerland, /2/)

Important applications of MST elements

The search for new solutions through MST, concentrated naturally on miniaturization "Bottlenecks" regarding important modern systems like e.g. ink jet printers or airbags. From this new solutions have been developed for:

- Integrated acceleration sensors and pressure sensors, see illustration 1.
- Angle rate sensors for driving dynamics regulations of cars (keyword "moose - test")
- Micro nozzle systems for ink jet printers

Due to the research results already obtained today, good chances exist that in the next years, with the MST in the following areas new system approaches will become possible:

- Integrated, multidimensional angle rate sensors
- integrated "High q" elements, such as resonators (replacement SAW, quartz)
- micro valves, micro pumps (medical technology, chemical analysis/synthesis procedures)
- miniaturised gas analysis devices for cars and air
- chemical micro laboratories
- micro-surgical tools
- micromechanical machines with 3D-MST form elements, see illustration 2.

MST uses "micro physics"

Naturally, the same physical laws as for conventional elements apply to MST. However physical effects in amazing new developments and applications can be used through the miniaturised designs with their smaller dimensions and masses. Here are the essential differences and the new possibilities:

- New field/force balance and/or other forces dominates:
  - Coherence and adhesive power gain significance, gravitation loses.
  - Electrostatic fields win, electromagnetic loose.
  - Surface tension of liquids, capillary action gains importance.
  - Tunnelling currents, atomic forces can be used purposefully (e.g.. AFM) /6, 7/.
- electro-thermal conditions: micro heating elements with time constants <1 ms
- flexible behaviour of normally "stare" materials (springs made of Si, glass)
- flow attitude of gases, liquids

All these effects are used in the micro system technologies and/or bred through technological measures and through a specific design of the elements in order to receive new economical system solutions. In the following the MST technologies will be dealt with in detail:

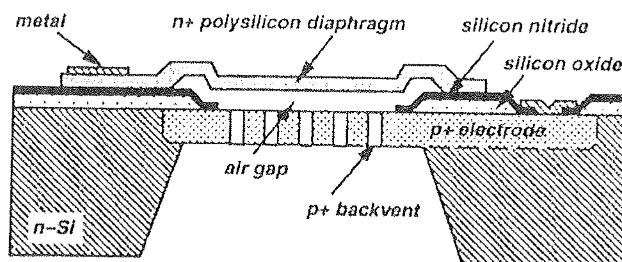


Fig. 3: Structure of a MST microphone in combined surface and Bulk Micromachining technology (Source: University of Michigan, Ann Arbor/14/)

MST Technologies and Materials

Surface and Bulk Micromachining (MM) technologies are a common extension of the silicon technology on MST elements. Particularly the surface MM is very well compatible with the IC technologies and therefore extremely suitable for smart sensors and actuators. Surface MM and Bulk MM can be partly used in a combined way, as shown in fig. 3.

Bulk MM means that parts of the SI substrate are etched away and/or free etched. The etching in general takes place from the back. Usually KOH or TMAH is used for this purpose, which have anisotropic etching characteristics. The issue of the etching stop is essential in order to achieve high manufacturing security. For this purpose pre-polarised pn-junctions (electro-chemical etching stops) or also SiO_2 layers can be used. TMAH as etching stops is of particular advantage with SiO_2.

Surface MM means the production of micromechanical structures at the Si surface. Several kinds of microsensors (acceleration/pressure and gyroscope sensors) can be realised by structured Poly SI layers on Si circuits. The used Poly Si layer thickness amounts to between 2 and 7 µm. The structures are usually manufactured and free-etched with plasma etching technique (RIE: reactive ion etching). Height/width conditions to 3.5 can be realised thereby. Thin structures permit the flexible suspension of Poly Si structures, which are usually electrostatically moved and/or put into oscillation.

For many kinds of MST elements it is necessary to realise larger heights and/or height/width conditions as well as to use further materials such as Ni or plastic polymers. For this purpose a special manufacturing method /8/ called "LIGA" was developed at the Research Centre Karlsruhe in the 80's. It is based on a Roentgen depth lithography, which permits 1mm high structures with accurately perpendicular walls under the application of parallel synchrotone radiation, as well as on a galvanic process for the placing of thick metals (Ni, Au, Cu) and on a plastic casting technique. LIGA allows the precise production of microstructures high over 1mm with height/width conditions up to 500. LIGA is therefore a particularly suitable, in many varieties world wide applied process regarding MST elements for electrostatically steered lateral microsensors of highest quality as well as for microactuators.

In the research stage there are further processes which permit the production of genuine three-dimensional structures /2, 3/. Usually stereolithography on a UV basis is used for this purpose. Future applications are to be looked for in the field of micromechanics.

As a contrast to these highly complicated structures an extremely simple technology gains importance with MST in various applications: Micro heating elements. They usually consist of thin Poly Si filaments /9, 10, 11, 15/. Applications for inkjet printheads show that with MST based heating elements time constants in the sub ms range can be achieved. So far only monolithic manufacture procedures have been described, but naturally with MST multi-layer-processes play a very large role /4/.

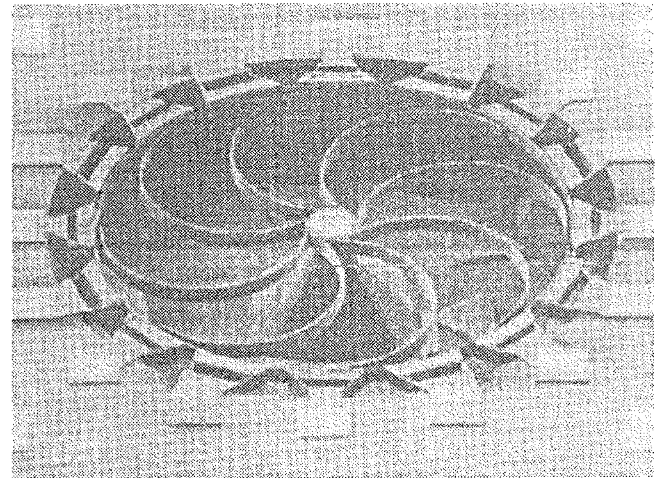


Fig. 4: MST Turning Rate Sensor with vibrating Poly Si ring (Source: University of Michigan, Ann Arbor, /12/)

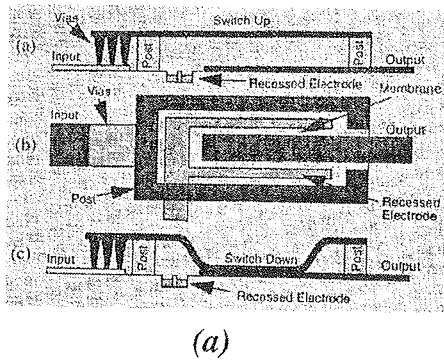
MST-Examples for Application

The variety of applications and realisations of microstructured sensors and actuators makes a general presentation impossible. Particularly promising for their economic marketing appear those MST concepts, which can be connected monolithically with integrated circuits. From this monolithic integration additional technical advantages result like e.g. fail-safe characteristic or calibration possibilities. Therefore sample applications of two of these promising, integrable realisation concepts are given:

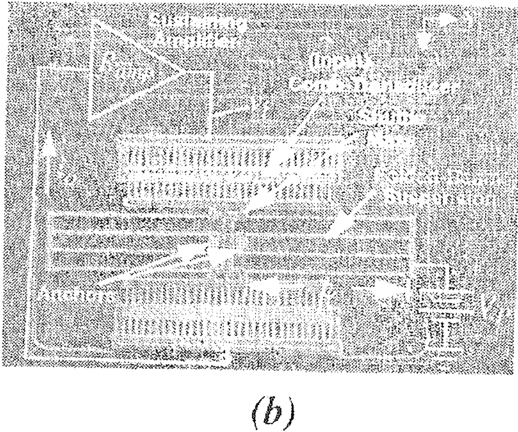
a) **Vibration-/Resonance Method**: Oscillation-capable structures from Poly Si, hung up at flexible Poly Si carriers and steered by reciprocal effects over electrostatic forces with fixed appropriate Poly Si plates can be applied easily on CMOS or BIMOS IC's. The same technology is already applied today in acceleration or pressure sensors or MST microphones (fig. 1). It is, however, unbelievably versatile.

   Gyroscopes ("Turning Rate Sensor"): Fig. 4 shows a gyroscope, a kind of "gyroscope compass" with which the rotating motion is replaced by a vibration moment. First prototypes of these sensors are already used in automotive electronics of Mercedes, in order to make the vehicles "moose test suited". Their anchor is shifted electrostatically in oscillation, separate Sens electrodes determine rotations caused by Coriolis forces with rotating motion of the sensor. The obtained resonant frequencies lie between 1 kHz and 30 kHz. /12/.

   "High-Q Elements": These are electromechanical elements, which are needed for tuneable filters or resonators with highest quality. Oscillationable structures, which can be manufactured in an integrable way in S-MM Technology, are also suitable for this purpose. Fig. 5 shows the principle and the realisation of a 16.5 kHz oscillator in MST technology. Even if today the performance data of SAW or quartz elements have not been reached yet, this new technology offers substantial potentials for future HF communication systems.

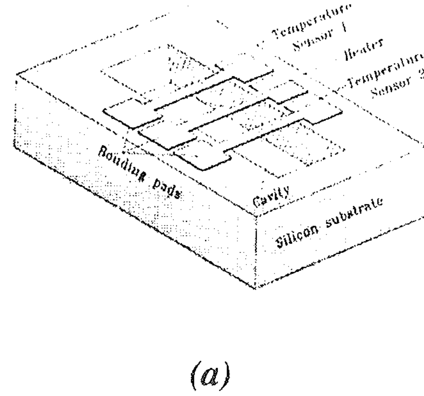


(a)

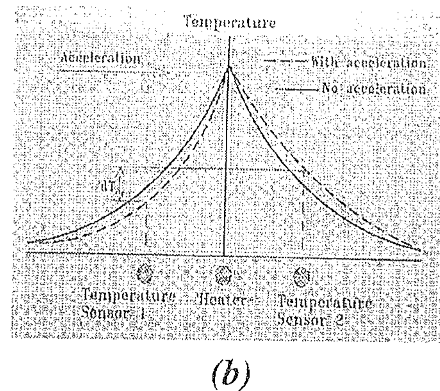


(b)

Fig. 5: Structure of principle (a) and realisation (b) of a 16.5 kHz CMOS μ-resonator (Source: University of Michigan, Ann Arbor)



(a)



(b)

Fig. 6: Thermal convection acceleration sensor (Source: Simon Fraser University, Burnaby, CDN /11/)

b) **Micro-heating elements**: Thin Poly-Si filaments, embedded into isolating layers (e.g. SiO_2), permit the development of completely new applications with mechanically durable elements equipped without mobile parts. The microscopic order of magnitude makes it possible to operate these micro-heating elements with a minimum of power (mW range) as well as to reach fast response times (several hundred Hz) for thermal processes. The technology can be realised in a very simple and cheap way and is completely compatible to IC processes.

Thermal acceleration sensor: The acceleration sensor shown in fig. 6a distinguishes itself by a completely different operational principle compared to today's MST realisations. The shifting of the temperature distribution of a gas (fig. 6b) in a micro-structured cavity is differentially evaluated in this symmetrically developed sensor.

3D-Flow sensor: In the sensor shown in fig. 7 the cooling of micro heating elements is used for the evaluation of flow conditions. The speciality of this sensor is the arrangement of 3 heating filaments in x-, y- and z- direction. For the additional deflection of the z-filament a special "Temper" process is used in connection with the Polyimid suspension of this filament. A further possibility for such figurations represents deflection in a magnetic field with the Lorentz power /16/.

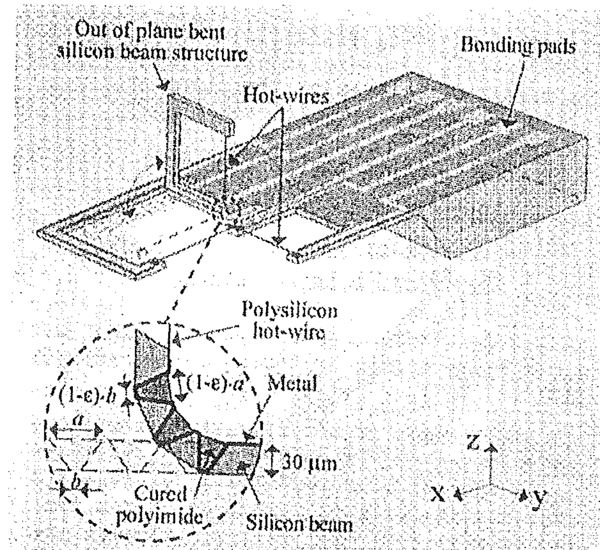


Fig. 7: Thermal flow sensor with 3D-Heating filaments (Source: Royal Institute of Technology, Sweden, /15/)

Final remarks:

Micro-system engineering is an up and coming, innovative branch with growth chances like microelectronics, which offer possibilities also for small and medium sized enterprises. In the overview shown, which must remain incomplete due to the variety of the MST area, the attempt was made to work out essential, promising operational principles and important development tendencies. Microsensors and microactuators will shortly be a natural component of many miniaturised systems. The combination of these elements with integrated circuits appears to be particularly attractive.

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