Microactuators - Principles, Applications, Trends

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Abstract

With the aid of actuators energy fluxes and mass or volume flows can be controlled electrically. Microactuators distinguish themselves by dimensions in the range of millimetres and submillimetres. This paper describes the technologies prevailing today for the manufacturing of microactuators. A wealth of examples from the most different application fields clarify their application potential as stand-alone devices and in microelectro-mechanical systems (MEMS).

1 Introduction

1.1 Principle

Microactuators are based on three-dimensional mechanical structures with very small dimensions which are produced with the help of lithographic procedures and nonisotropic etching techniques. For an actuator-like displacement the most different principles of force generation are used, such as the bimetal effect, piezo effect, shape memory effect and electrostatic forces. Characteristic for microactuators in a more narrow sense is the fact that the mechanism of force generation is integrated monolithically; in a broader sense, however, also microstructures with a not monolithically integrated force generation are numbered among microactuators.

With the down scaling of the actuator dimensions from the macro-range to the micro-range of course also the actuator forces decrease. When m is the reduction ratio of a mechanical structure, electromagnetic forces - depending on the technical requirements - are theoretically reduced by the ratio of up to m^4. Pneumatic, hydraulic or biological (muscle) forces and even surface tensions behave in a more favourable way because they decrease only by m to m^2. Electrostatic forces are of particular importance in the micro range: They decrease with m^2, but as the breakdown electric field strength in insulators increases with decreasing dimensions (Paschen effect), the electric field strength may be increased by $m^{-0.5}$ which leads to a reduction of the forces by only m.

1.2 Realisation

For the manufacturing of extremely small mechanical components with movable structural parts there are in essence the classic micromachining based on single-crystal silicon, surface micromachining for the production of polycristalline silicon structures, and the LIGA technology; furthermore there are precision engineering techniques such as electrical discharge machining (EDM) and micro injection molding.

The well-known silicon technology is the obvious manufacturing procedure as silicon can be produced at highest purity in sufficient quantities at low costs, and many procedures can be taken over from micro-electronics. Furthermore, single-crystal silicon has also good mechanical properties; e.g. Hooke's Law is valid at strains ten times higher than in other materials. Apart from that silicon easily enables the monolithic integration of electronic components, e.g. control circuits or monitoring sensors ("intelligent actuators"), whereby several hundreds of components per wafer and process can be manufactured simultaneously (batch processing). Existing surface micromachining technologies on the bases of polycristalline silicon in combination with a silicon oxide sacrificial layer technology (SLT) have been qualified for up to 5 levels.

The LIGA technology, a combination of lithography, electroforming and replication processes can be used for the cost effective fabrication of high precision microstructures from a large number of polymers, ceramics and metals or metallic alloys. The generation of the primary structures in thick resist layers by deep X-ray lithography can be replaced in certain cases by other microstructuring techniques, such as laser or particle beam based processes. The polymeric primary structures are transformed into a metallic secondary structure by electrochemical deposition processes, which may be used as molding or embossing tools in various types of replication processes.

However, many "classical" materials for chemical technology can only be microstructured by extending conventional precision engineering techniques into the micro regime. In particular micro milling, using diamond tools and high speed spindles, as well as spark erosion based techniques have been used successfully for the fabrication of microfluidic components. In many cases technically and economically optimized solutions can only be realized by a combination of different fabrication techniques. Very promising results have been achieved, for example, by the use of high precision LIGA-fabricated Cu electrodes in a micro die-sinking erosion process.

2 Microdrives

High precision drives with millimetre size have become a key element for minimal-invasive diagnostics and surgery as well as for miniaturized scanners in datacom or positioning drives for example micro robots and hand held consumer devices.

2.1 Electromagnetic micromotors

The micromotor in **Fig. 1** consists of a diametrically magnetized rare-earth magnet rotor surrounded by a coil system, which generate a rotating magnetic field.

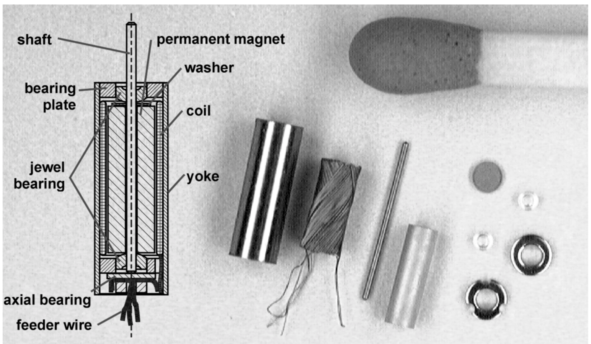

Fig. 1 Construction and components of a 1.9 mm motor [1]

A softmagnetic tube simultaneously acts as housing and return yoke for the magnetic flux. In order to minimize the outer diameter of the motor a yoke material combining a high saturation magnetization and a very low coercivity has been chosen. This motor design leads to comparatively small heat losses and a lower power consumption. With its diameter of 1.9 mm and a length of 5.5 mm the motor generates a considerable torque of up to 7.5 µNm and rotational speeds of more than 100,000 rpm. All mechanical parts are fabricated by conventional precision engineering methods [1,2].

In addition to the longitudinal type a penny-shaped electromagnetic motor as thin as 1.4 mm was developed (see **Fig. 2**). The rotor contains 8 permanent magnets and a soft magnetic return yoke which encloses the flat coil array in the stator. The magnetic simulation shows how the ball bearing can be pre-stressed by an additional softmagnetic ring in the stator in order to avoid yaw motion of the rotor axle. Furthermore, a magnetic scatter field hardly appears. Due to the very small radii extremely high accelerations and rotation velocities up to 60,000 rpm in continuous operation are reached. The motor torque scales almost directly to the volume and ranges up to 100 µNm [1,3]. For series fabrication of the motor,

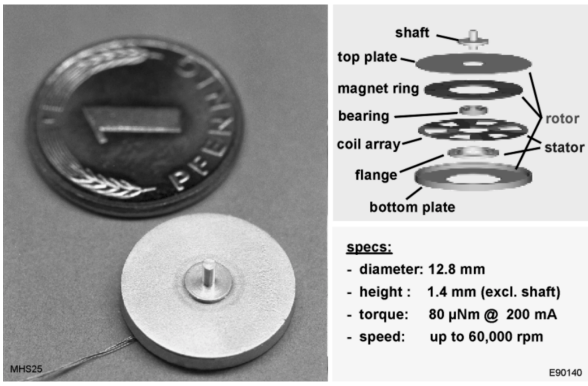

Fig. 2 Construction and realization of the penny motor [1]

precision engineering technologies are combined with micro techniques which are advantageous for coil arrays, electrical interconnection and encoders. Recently, a family of penny-shaped micromotors has been developed.

2.2 Reduction gears

In order to adapt the high speed of micro motors to the industrial requirements of 100 to 5,000 rpm and in order to increase the output torque considerably, miniaturized reduction gears with similar sizes and shapes are needed.

A gear realized for the 1.9 mm motor is a three-stage gear and contains plastic parts fabricated of POM using the LIGA technique, see **Fig. 3**. For mass production a through-going batch process has been

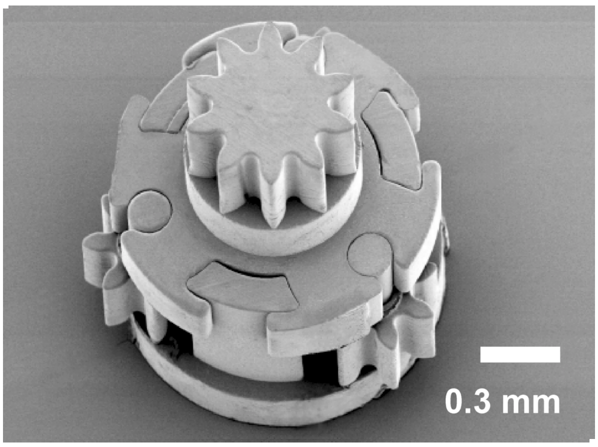

Fig. 3 Stage of the planetary gear. Gear modulus 55 µm. Gear stage ratio: 3.6 [1]

developed where hundreds of gear components are molded simultaneously in a wafer-like magazine. Each stage is assembled separately. The gear may deliver an output torque of up to 300 µNm in short-time and 150 µNm in continuous operation [1,2].

The penny motor (Section 2.1) with its flat shape is perfectly suited to miniaturized rotary positioning systems, if a flat gear with high ratio and zero backlash is integrated. Therefore, the harmonic drive with dynamic spline as output proves to be an excellent solution but extremely difficult to miniaturize. By realizing the wave generator by a simple planetary gear with two flexible planets the overall diameter could be kept as small as 8 mm and a gear ratio of 505 – in one stage – could be achieved. High aspect LIGA technique turned out to be the pre-requisite to realize the prototype shown in **Fig. 4**, which is illustrated impressively especially by the flex spline. Its inner and

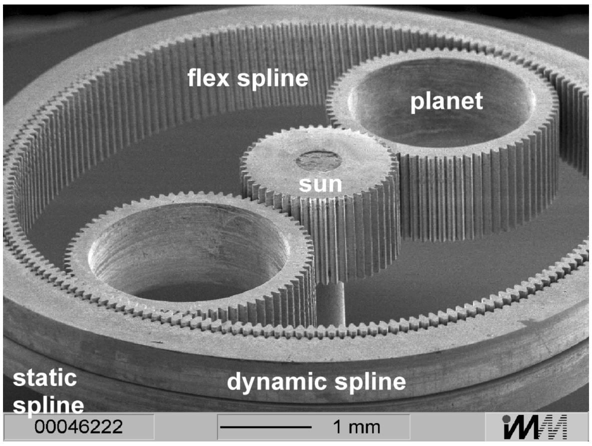

Fig. 4 Micro harmonic drive. Gear moduli: 34 µm and 35 µm resp. Gear size: ∅ 8x1mm^2. Gear ratio: 505 [1]

outer toothing have moduli of 34 µm and 35µm respectively. While the tooth width is as high as 1 mm the ring thickness amounts to only 40µm. That means an aspect ratio of 25 is achieved [1].

The examples described show that miniaturization of reduction gears down to millimetre size can be achieved by applying the LIGA technique. The development may be executed step-wise by using high aspect ratio lithography and electroplating steps for prototypes and, eventually, injection molding for series production.

3 Positioning and gripper systems

Miniaturized linear positioning systems have turned out to be a basic unit for a wide range of applications. Examples are robots and grippers for the production and handling of semiconductors and optical fibres, means for positioning, adjusting, focussing or zooming of lenses or fibre-optics in datacom, telecom or consumer products and the manipulation of cells and tools in medicine and biology.

Common modes for individual actuation are electrostatic, piezoelectric, electromagnetic and electrodynamic. Pneumatic actuation is also an interesting approach. When large displacements are needed, a thermal actuation is favoured.

3.1 Positioning systems

A micro positioning device has been developed that obtains a closed-loop control including an incremental optical encoder which directly gauges the slider motion [1]. By applying modules like the micromotor (Fig. 1) and planetary gear (Fig. 3) and ultra-precise fabrication of steel slider and housing by wire EDM, the performance was considerably increased: 40 x 6 x 4 mm^3 overall size, 20 mm travel range with a velocity of up to 400 mm/s, a force of up to 0.75 N and a positioning accuracy of ± 5µm.

Using the electrostatic mode for comb-drive actuation much progress has been made especially with respect to the displacement and linearity. **Fig. 5** shows the SEM photograph of a sensor-actuatorsystem for application in Atomic Force Microscopy (AFM). Within this system an electrostatic actuator, a capacitive sensor and a silicon tip are included. The actuator is designed to generate a large lateral displacement of about 20 µm. The system is active positioning within this range and enables nanometer resolution. Further applications of the low-force electrostatic principle are focusing on positioning/ displacement of opto-mechanical components like switches, attenuators and filters or even microlenses.

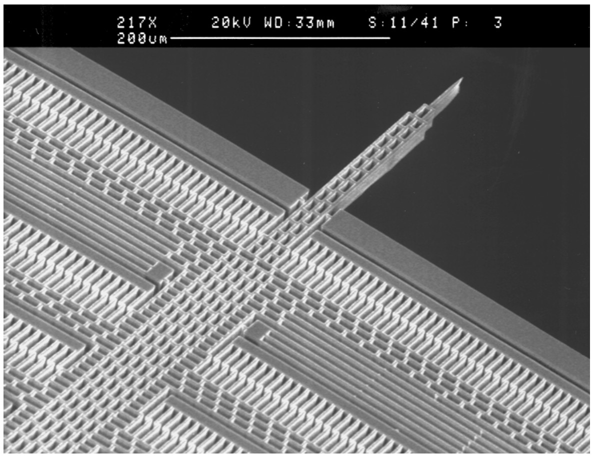

Fig. 5 SEM detail view of an electrostatic silicon actuator with integrated tip for lateral AFM measurement [4]

3.2 Gripper systems

In the last decade a few micrograppers have been built. Mechanical gripping, gripping by vacuum, gripping with adhesive substances, magnetism and electrostatics are the main principles which are applied. The only tool which is applicable almost everywhere are mechanical grippers. For those grippers various physical effects are used to generate the movement and the gripping force such as electromagnetism, electrostatics, piezoelectric and shape memory effect [4].

Salim developed a gripper (**Fig. 6**) which is actuated by monomorphic piezoelectric ceramic. The gripper

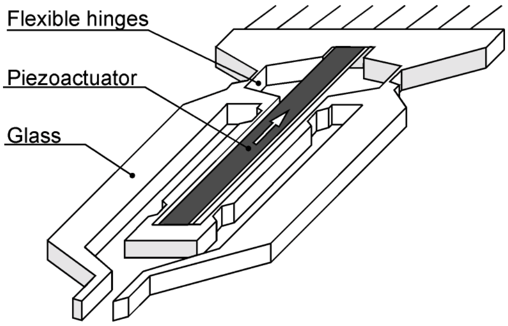

Fig. 6 Scheme of a microgripper made of silicon or glass [4]

was made of silicon or photosensitive glass [4]. The necessary hinges are solid-state hinges. The piezoelectric actuator is firmly connected to the gripper. When voltage is applied, the actuator contracts and thereby moves the gripper. The displacement of the piezoactuator is amplified by the solid-state hinges and the arms of the gripper up to 100 times. The total system achieves a gripping force of 20 mN and a gripper-jaw displacement of 100 µm.

Fig. 7 shows a scheme of an SMA microgripper in open and closed condition [5]. The gripper is mounted on a substrate in a pre-strained condition. Thus, a deformation is created in the beam structures, which can be controlled by electrical heating. By selective

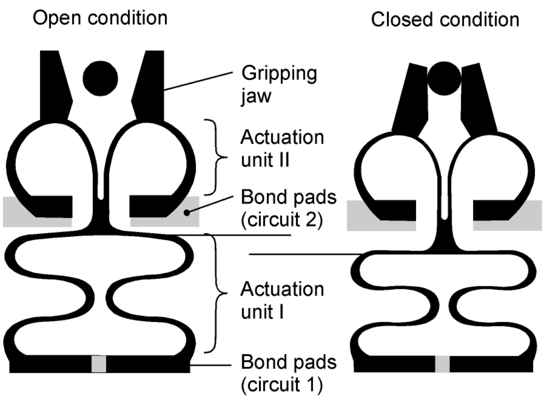

Fig. 7 Operation principle of a shape-memory alloy (SMA) microgripper [5]

heating of actuation unit I above the phase transformation temperature, the folded beams recover their undeflected memory shape, which leads to a linear motion of the link. Consequently, the circular beams are deformed and the gripping jaws are closed. This condition can be reset by selective heating of the circular beams (actuation unit II). The link between the actuation units is designed to provide sufficient thermal isolation.

This microgripper has been fabricated by laser cutting of a cold-rolled sheet of TiNi of 100 µm thickness. For a prototype with 2 x 3.9 x 0.1 mm^3 size the gripping jaws allow a maximum stroke of 180 µm and a maximum gripping force of 17 mN. A typical response time is 32 ms for 22 mW electrical driving power. The cooling times are considerably longer, in the order of 300 ms. However, due to the used antago-nism the response times for opening and closing are only determined by the heating performance of the corresponding actuation unit. The cooling performance determines the maximum frequency of actuation cycles.

4 Microoptics

Optical applications are a major sphere of actuator devices. For instance microlenses are positioned and focused, mirrors are actively shaped to a certain curvature and micromachined gratings with electrically controllable transmissions have been investigated in the past years.

4.1 Microscanners

Microscanners have been reported frequently in connection with a great variety of applications ranging from barcode scanners to scanning image projection with laser. Arrays of micromirrors, developed up to several millions of cells, are used for optical signal processing and image projection or they act as phase grating respectively.

The principal structure of microscanners is a tilting, movably suspended mirror plate, attached to a substrate (see **Fig. 8**). On the one hand, the rotational stiffness of the hinges and the mass moment of inertia define the resonant frequency and often the maximum working frequency likewise. On the other hand, the stiffness of the suspension determines the required driving force for the application dependent maximum tilt of the mirror. Driving near resonance increases the tilt by the Q-factor up to several hundred.

Torsion beams are primarily used for elastic suspension in case of one-dimensional scanners. However, for two-dimensional scanning devices gimbal structures or specially shaped hinges are necessary. The hinge material depends on the fabrication technology. Bulk-silicon, poly-silicon, various metals (Ni, Al) and polyimid are used.

Electromagnetic, piezoelectric, electrostatic, and thermal driving have been reported [4]. Most of the mirrors are electrostatically driven, whereby maximum

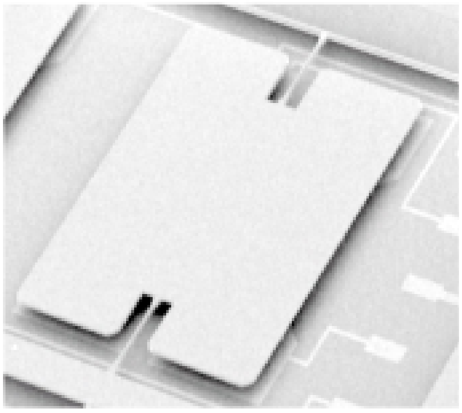

Fig. 8 SEM view of an electrostatically driven scanning mirror [4]

working frequencies of 250 kHz are possible. Voltages of up to several hundred volt are necessary depending on mirror size, maximum tilt and resonance frequency. The working frequency of thermally actuated optical microdevices is limited to less than 1 kHz by thermal capacity.

4.2 Microchopper

Detector arrays in spectrometer systems for the near-infrared range must be operated on modulated light to achieve sufficient high signal-to-noise ratios. To realize a handheld infrared spectrometer, a miniaturized light modulator has been developed [6].

The set-up of the microchopper with lateral dimensions of 3.0 x 3.2 mm^2 is shown in **Fig. 9**. The LIGA structure of electroplated permalloy with a height of 280 µm is supported by an aluminium oxide ceramic substrate. The stop can oscillate at one end of two rectangular parallel springs with a width of 10.8 µm. They are fixed to the substrate at the other end. The stop also constitutes the anchor of the magnetic actuator. It moves between the two poles of the chopper core with an air gap of a few micrometers. These two parts are structured monolithically on the substrate. The resonance frequency is approx. 1 kHz.

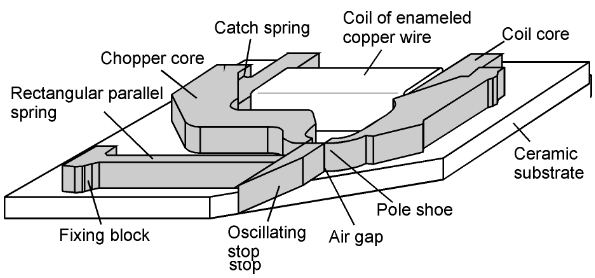

Fig. 9 Setup of a microchopper [6]

The coil is inserted during assembly and fixed with catch springs. It consists of a permalloy core with several hundred windings of enamelled copper 15 µm in diameter. When a current flows in the coil, the stop is attracted by the core independently of the sense of current. For a periodic current, this leads to an oscillation of the stop at twice the frequency of the current. This is a major advantage for use in the microspectrometer system.

5 Microfluidics

Microfluidic components and systems are currently gaining industrial significance in various technical fields, medical technology being among the most prominent. However, the need for miniaturized fluid handling systems is becoming even more pronounced in chemistry and biotechnology.

5.1 Microvalves

There is a growing demand for miniaturized valves in a wide range of applications: Valves in cold gas jet systems applied for space applications need to be lightweight and should deliver an ultra-short response time. Valves for printing devices or for chemical micro reactors must be small and cheap because a high number of valves has to be arranged in large arrays.

A promising approach which solves the mentioned requirements is shown in **Fig. 10** [1]. In closed state, a ruby ball, which is commercially available down to a diameter of 300 µm, is pushed against the valve seat by the fluid pressure. To open the valve, the ball is flung into the valve cavity by hitting the valve seat with a piezo stack. When piezo actuation is finished, gas pressure of up to 2,000 hPa pushes the ball back in less than 1 ms. The valve seats are made of silicon by advanced silicon etching in a wafer process. For the machining of the housings a combination of micro die-sinking and wire EDM is used which allows a series production in steel.

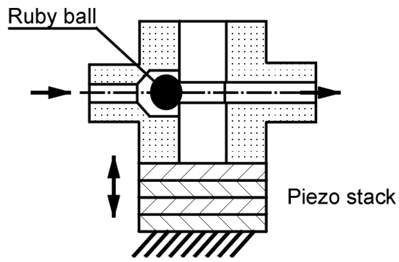

Fig. 10 Principle of a micro ball-valve [1]

The valve in **Fig. 11** has been designed for operation in a normally open condition where the pressure acts as a biasing force against the actuation force generated by the SMA device. A polymethylmethacrylate (PMMA) substrate of 10 x 20 mm^2 lateral size has been processed by mechanical micromachining to establish a pressure chamber with inlet and outlet ports A and B respectively. The microvalve has been designed for a maximum pressure difference of 1200 hPa. At this pressure limit, a stroke of 70 µm, a gas flow of 1600 sccm and a workoutput of 35 µm have been observed. The typical response time for closing the valve is 0.5 s, the cooling time is 2 s [7].

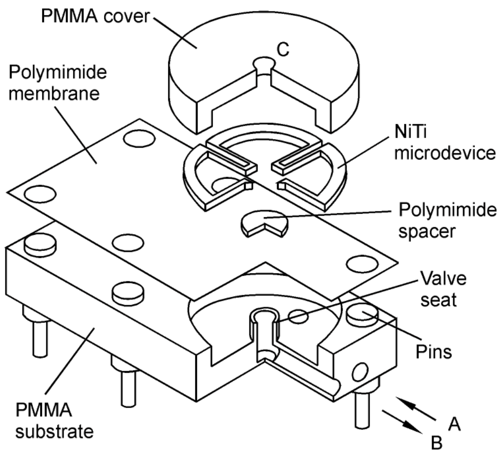

Fig. 11 Cross-section of the microvalve. A, B and C denote valve ports [7]

For improvement of the work output, the SMA microdevice has been stress-optimized. The basic idea of stress optimization is to design the shape of active SMA parts in such a way that spatially homogeneous stress profiles are obtained for a given load pattern. Thus, a maximum volume fraction of SMA material is used for actuation, and fatigue failure due to local stress maxima is minimized.

5.2 Micropumps

Micropumps are attractive means for drug dosing in medicine, reagent delivery on chemical applications or adhesive dispensing in the semiconductor industry. Furthermore, new application fields arise for dosing of lubricants for machine tool bearings or with pump arrays for high-throughput screening in chemical analysis.

The pump principle shown in **Fig. 12** is realized by silicon machining in many places. However, costs

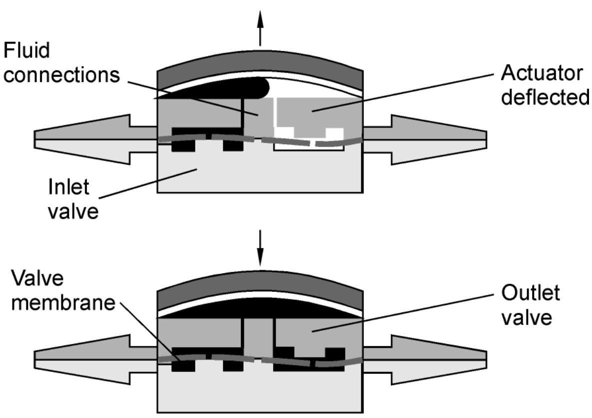

Fig. 12 Principle of the micro membrane pump [1]

remain considerably high due to the large lateral size of 10 to 20 mm. Cost-efficient series production has been achieved by switching to polymers like PC, PEEK or COC. The top and bottom parts, which are injection joined, and membrane foils are connected hermetically by laser welding. Finally, the bimorph piezo plate is glued onto the outer foil. The self-filling membrane pump is commercially available. Maximal pressure and maximal flow rate are up to 2,000 hPa and 0.4 ml/min for water, as well as up to 500 hPa, down to -350 hPa (vacuum) and up to 3.5 ml/min for air [1].

The self-priming and bubble-tolerant operation mode was achieved by enlarging the compression ratio - the stroke volume of the actuation divided by the deadvolume of the pump chamber - of the micropump. A compression ratio of about 1:9 could be attained, which allows pumping of liquids and gases as well as of liquid/gas-mixtures [1,8].

Fig. 13 demonstrates mechanisms to transport highly viscous fluids even with solid particles by the roll off

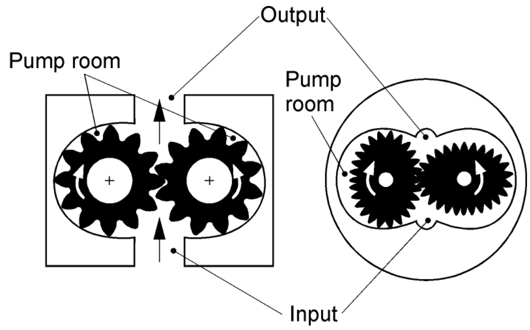

Fig. 13 Principles for micro gear pumps with an external gear pair [1]

of two gear wheels. The pump with the oval wheels provides a larger pump room which increases flow rate and allows a higher size of solid particles or a more careful delivery of sensitive fluids like blood.

A prototype of the circular pump has been realized by using LIGA wheels with a modulus of 38 µm and a brass housing which was conventionally milled. Tests of the gear pump show a linear relationship between flow rate and rotary speed of the wheels, while pressure hardly has an influence on the flow rate. For a mixture of glycerine and water a maximum flow rate of 170 µl/min could be achieved at 2250 rpm up to a pressure of 1,000 hPa.

5.3 Fluidic microsystems

The dramatically increasing number of syntheses and analyses in current biotechnological and pharmaceutical development processes can only be performed by highly automated processing systems using extremely small reagent quantities. Miniaturization is an essential prerequisite for the necessary enhancement of the performance of reaction and analysis systems by integration and parallelization of many procedural steps.

Successful construction of complex biotechnological processing systems, e.g. for mass screening or combinatorial synthesis methods, requires the use of reaction chambers, mixing and heat exchanger systems, separation devices, pumps, valves and many types of sensors with extremely small dimensions [9,10]. Interlinking of microfluidic components in a micro-channel system produces complex microliquid handling systems, see **Figure 14**.

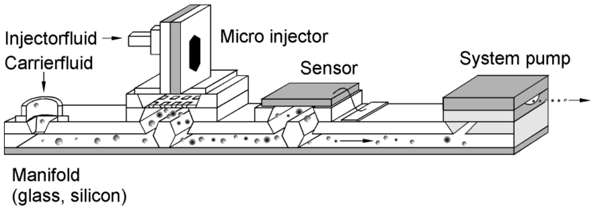

Fig. 14 Cross-view of a microliquid handling system [10]

The layout of fluidic microsystems orientates itself by the advanced designs of hybrid technology. This orientation is useful, as the building-up and bonding techniques of hybrid technology are particularly suitable just for the interfacing of components strongly differing in material and geometry. When having a look at the large number of microfluidic components which have been developed so far, the significance of the fluidic microsystem technology as a technology which is able to interlink these components within the microsystem efficiently, robustly and reliably becomes comprehensible.

6 Outlook

Since the 90s the microactuators have been conquering new fields of applications - not least because the manufacturing technologies have reached a high degree of ripeness. In spite of this, an enlargement of their application potential requires particular obstacles to be eliminated: For example, in most cases the control electronics is still much more voluminous than the actuator element itself. Thus, one development target consists in integrating the electronics in the actuator housing when possible [8]. In this context first experiences have led to an unexpected result: The development of a special ASIC often turns out to be the second choice. By a slight redesign of the mechanical and fluidic construction, standard electronics can be applied which reduces costs considerably [1]. Another impediment to application is due to the fact that users who could employ microsystems with great advantages for small and medium-sized series, rightly shy away from the high development costs. Application fields like these then also remain closed to the producers of microsystems. For this reason, industries and research institutes (in Germany, for example, under the umbrella of the VDMA) deal with the idea of realizing small quantities to be manufactured as well as huge production lots in a unit-assembly system labelled “microsystem technology”.

Acknowledgements

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