MICROMECHANICAL COMPONENTS FOR μTAS

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0. Abstract

The Modular Fluid System (MFS) concept as base system for the realization of Micro-TAS, as well as a number of different micromechanical components for use in Micro-TAS are presented. The correspondence of MFS to electronic breadboards is discussed, and an example of a possible "mixed" fluidic/electronic board is given. The consequences of downscaling for the operation of sensors in Micro-TAS are discussed, and a number of components, sensors, sieves, mixers, valves and pumps are presented. Finally, the importance of the development of design tools and rules, especially bondgraph modelling, for MFS is emphasized.

1. System approach

In this contribution we introduce the Modular Fluid System concept [1] as a generic Micro-TAS breadboard, comparable and additional to its electronic counterpart. We will treat the components or functions, necessary to build such a system. Systems may greatly differ in their specifications. This means that components must be available in a range to meet these specifications. Hopefully a set of components can be designed to meet this range, while on the other hand they fit into a system with standard interconnection rules.

If such a system is developed the most important function is the interconnection, which must be reliable, easy to reach and leakfree. One can think of a floorplan with a set of buried channels for fluids on one hand and a set of components that can be fixed between channel in- and outputs on the other hand. An impression of such a system with a floorplan and building stones is given in figure 1.

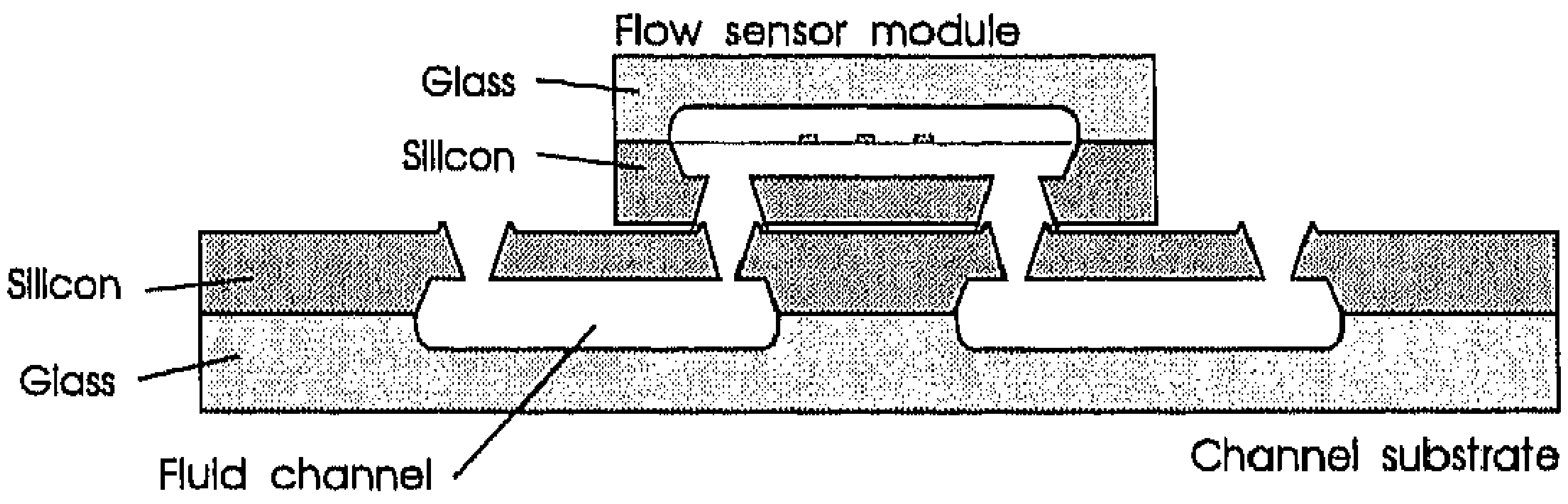


Figure 1. Flow sensor module on channel substrate.

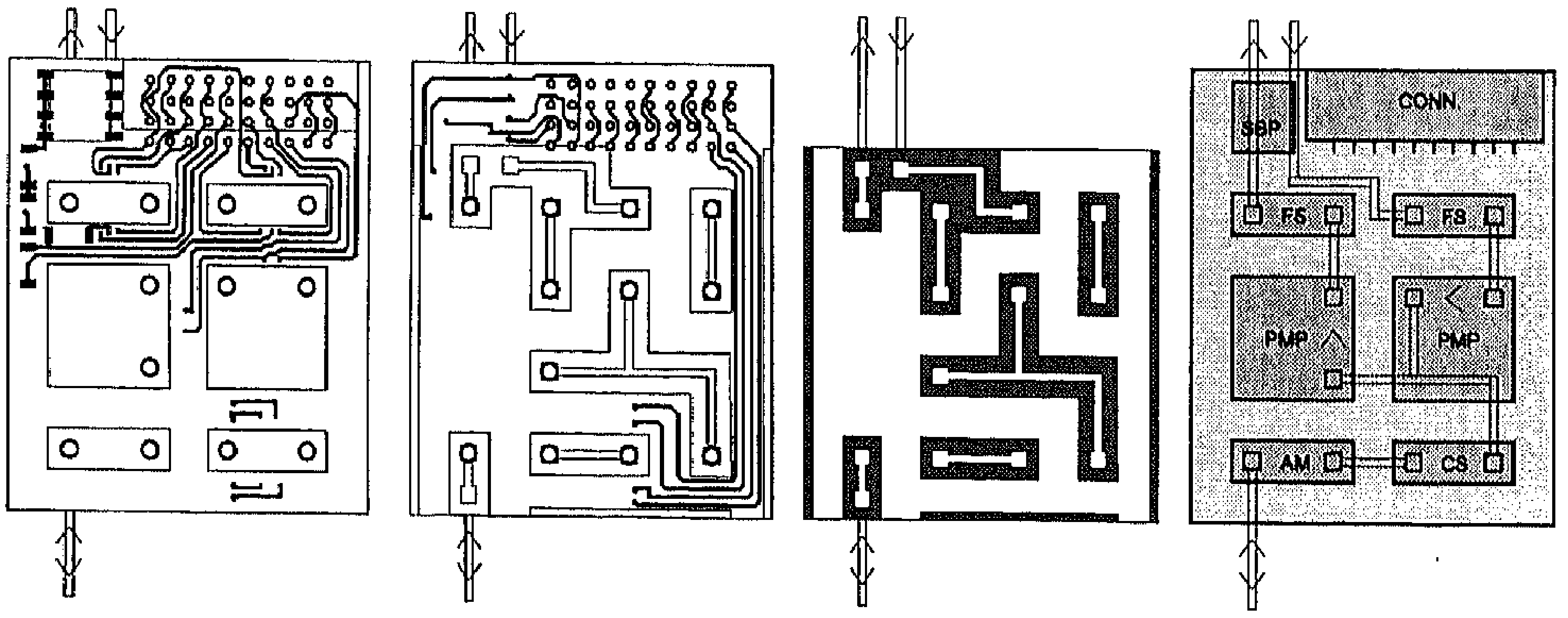
A. van den Berg and P. Bergveld (eds.), Micro Total Analysis Systems, 73–83.

The most simple component is the two-point link and its function is just to connect channels. Of course the floorplan will contain channels of varying lengths and directions, but it will sometimes be impossible to have all the desired channels in the floorplan. This will certainly be the case for many-point links. Think of a splitter, that connects the fluid flow from one channel into two or more other channels, or the reverse thereof. In principle these components are not difficult to fabricate.

More complicated components are supply buffers, (active) valves, (active) switches, pumps, sieves, fluid mixers, reaction chambers, sensor units (flow, pressure, temperature, fluid parameters like viscosity and density, chemical composition, etc.), separators, waste buffers, etc. The fluid in- and output ports generally are in the floor plane, but it might be necessary to have injection units and/or outflow units as components as well.

A general design rule for every system is, that is must be able to be filled up in order to reach the starting conditions. Undesired blocking of fluids as a consequence of gas bubbles in a liquid or of pieces of dirt, must be prevented. So, the total design might contain parts with a function to remove blocking objects and with a function to check the overall status of the system. This includes an alarm system to become active, when the system is not functioning according to its purposes. This means that, like in microelectronics, testable design is necessary. Additional components will be added to check, in the case of failure, what the cause of the failure is, and if redundancy is possible to switch the flow to another part of the system.

All components that have an interface to electronics, must have electrical connections. Factually, besides the fluid flow systems there must be a flow system for electric currents to connect the components to an output connector or to the bonding pads of IC's that are built on the system. So apart from the fluid flow channels the floorplan should contain a set of electrical connections and bonding pads. In Figure 2 an idea of such a mixed system is given.



PCB Top PCB Bottom Channel layer Component assembly

Figure 2. Schematics of floorplan with mixed electrical and fluid connections.

It is impossible to treat all possible elements in this contribution, therefore we have made a choice. The choice is based on relevance of the components, combined with the "in house" experience in our Institute. We will treat: sensors, sieves, mixers/reaction chambers, valves and pumps.

2. Sensors

2.1 CHEMICAL SENSORS

Although the chemical sensors are the crucial parts in a Micro-TAS, and are therefore extensively investigated in our Institute, it is impossible to spend much attention to them, because the chemical sensors form a separate and very extended field of research . Many conferences or conference-sessions are devoted to this subject and we have to refer to the proceedings and journals treating this subject.

However, the choice of the chemical sensors may have a large influence on the system as a whole. For instance we can have sensors with mainly a surface interaction with the fluid to be analysed, e.g. amperometric electrodes, or with a bulk interaction, e.g. in some optical sensors. In the case of surface-type sensors, the question is how much time T it takes to reach a stationary situation. Consider the reagent flowing with velocity V along the sensor. For $V=0$ the sheet thickness of the fluid S must be such that there is room for full development of static equilibrium in the desired time T. If $V \neq 0$ the supply of fresh fluid over the sensor leads to a stationary situation after a time T with a reduced sheet thickness required for a good measurement. So an increase of V, leads to a decrease of the required value of S, so that the product $F = VSB$, being the volume flow F for a channel with width B is less than proportional to V. If V is the determining factor for good sensing indeed, this means that a desired increase of V does not require a proportional increase of F.

The pressure difference Δp needed to reach a certain velocity in a thin slit is proportional with the reciprocal of S^2, while the volume flow F is proportional with the reciprocal of S^3B. So, in miniaturisation, the effect of V on Δp is two orders of magnitude less than the effect of F on Δp. This means that the requirements concerning pressures in a system, based on V-values are modest compared to mass injection systems based on F-values.

In the case of optical sensing this issue must be analysed for the case of "bulk" measurements, e.g. focusing a light beam through a fluid reservoir. Obviously, optical sensing methods based on the influence on the evanescent "light fields" along planar integrated optical waveguides, brings us again in the region of surface sensing techniques and the advantages thereof.

Of course there may be reasons, to pay attention to the minimum values of volume flows. It is conceivable that the flow velocities in low resistive connection elements becomes so small that other system requirements cannot be fulfilled, e.g. the number of analyses per hour, the procedures to clean the system and the suppression of sedimentation in dead corners.

2.2 PRESSURE SENSORS AND FLOW SENSORS

Pressure and flow sensors cannot be missed in a fluid flow system. Of course one can make use of well defined pressure and flow sources, but such sources relate their reliability on built-in pressure and flow sensors. Any pressure or flow source must be monitored for long term drift. (The same is true for the sensors, which must be calibrated by well defined sources: in the ideal case each actuator should have a calibrating sensor, each sensor should have a calibrating actuator.)

Pressure sensors mainly have monitoring and control functions in a Micro-TAS. But it is conceivable, that the pressure in a reaction chamber (e.g. as a function of time and/or concentration of the known reagent) can be used as an additional source of information about the chemical process and the ratio of chemical constituents. Silicon membrane pressure sensors of the type, which are widely used for automotive and medical applications are the most important candidates. We refer to the abundance of literature about these sensors. An example of the use of commercial pressure sensors of this type is given by the set up of the proposed fluid control system of Redwood Company [2].

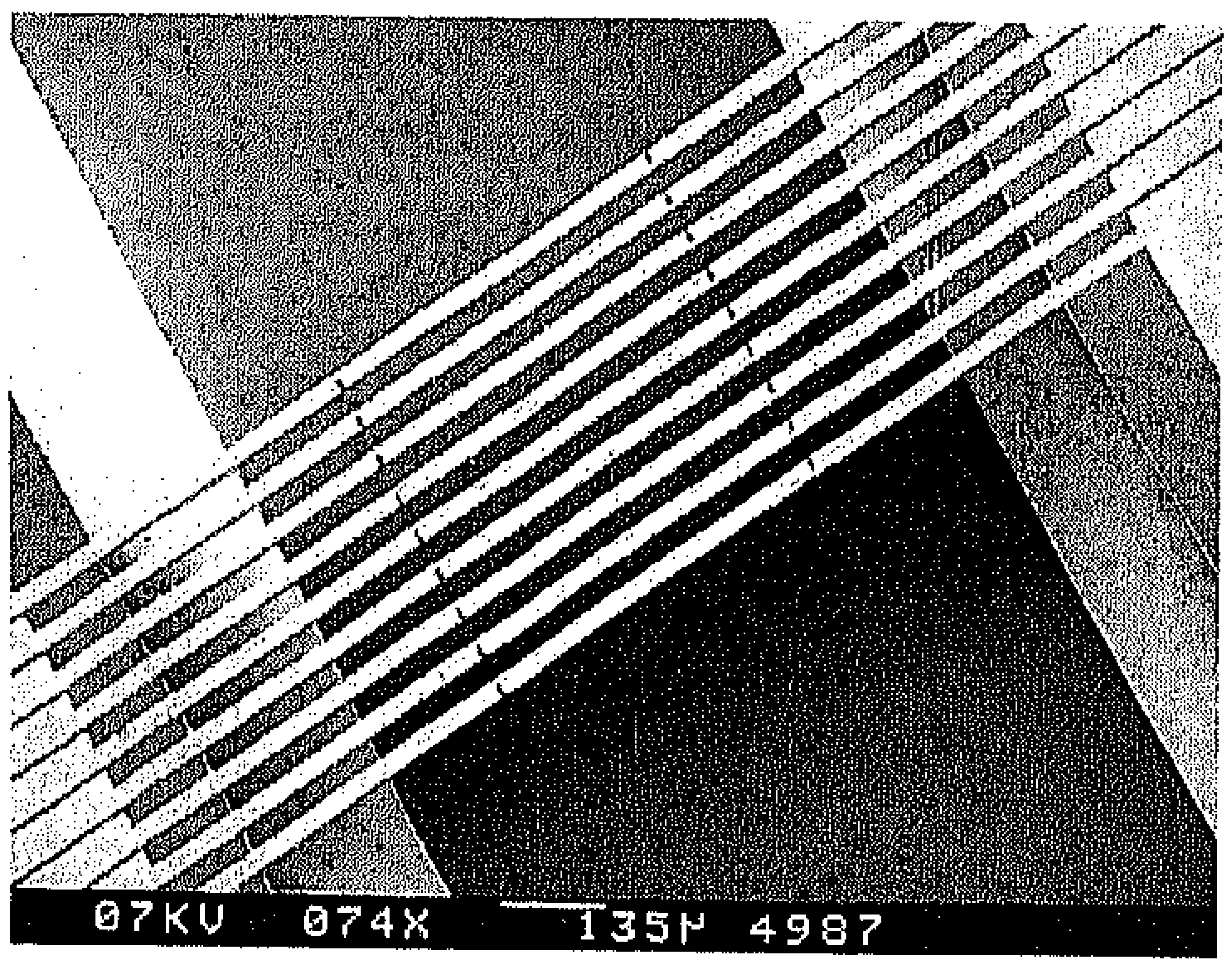


Figure 3. One dimensional multifunctional sensor/actuator array with 9 metal film resistors above the etched flow channel.

For monitoring purposes, use of pressure and flow sensors can be made to check for sedimentation in components, blocking of channels, and so forth. Accurate flow sensors are needed to check for the amounts of fluid involved. A very interesting type of sensor is the array sensor described by Lammerink *et al.* [3], see figure 3.

The array consists of a number of Si_3N_4 carrier bridges, 1 micron thick, 40 microns wide with a spacing of 80 microns. The bridges are covered with 200 nm metal films acting as resistive heaters or thermoresistive sensors, whatever the choice. Three of them are used in a standard anemometric sensor and two of them as a thermal time of flight sensor. Since these two types act in a different way on gas parameters it is possible two measure the mass flow as well as the composition of, say (used in our experiment), a He/N_2 mixture. An (artificial) neural network is used for the determination of the output values (figure 4).

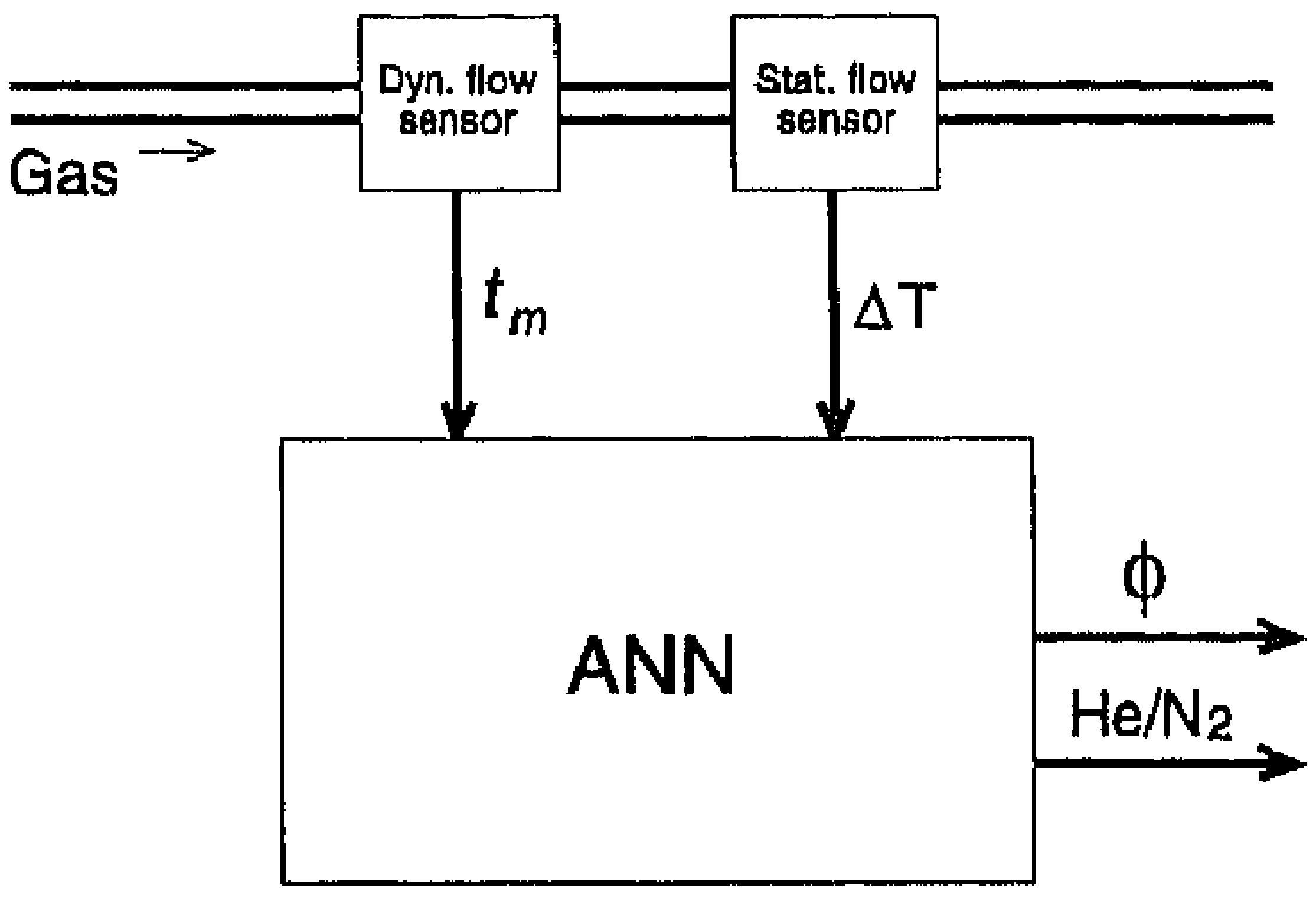


Figure 4. Artificial Neural Network (ANN) to determine flow rate and gas mixture indirectly from two flow-meters.

After covering the bridges with a thin noble metal film, they can also be used to measure heat developed by (bio)chemical reactions either in liquid phase or in the gas phase (catalytic converters) [4]. In the latter case, selectivity can be obtained by using different catalytic metals and by defining the working temperature of the resistors. In this way one can get accurate results from an array of sensors, where the elements themselves are not very selective (figure 5).

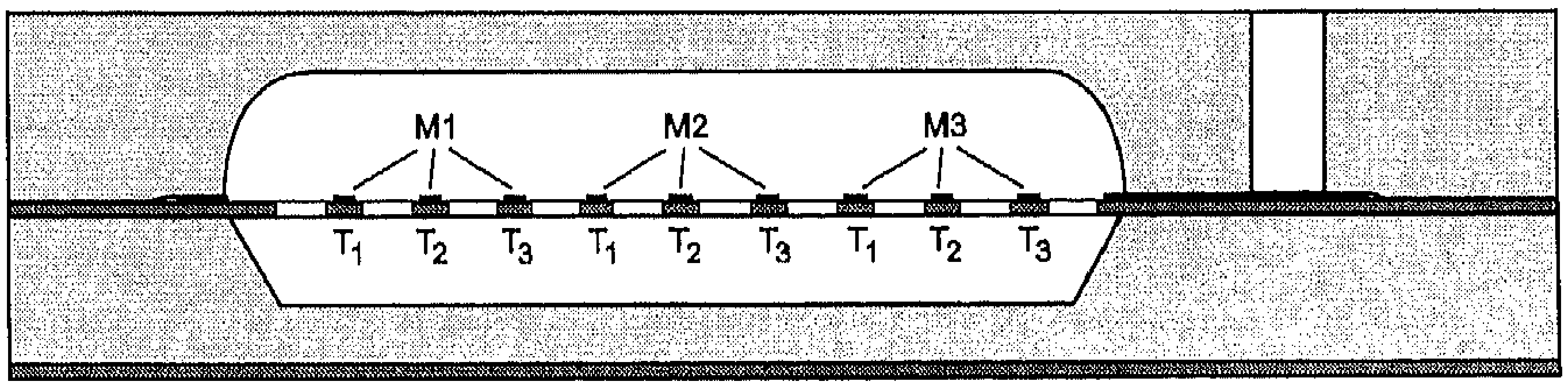


Figure 5. Cross-section of an array gas sensor with three different catalytic metals (M1-M3) and three different temperatures (T1-T3).

A matter of great concern is the durability of the sensors, in fact of any component in the system. Therefore it might be necessary to shield the sensors. It has been shown that Teflon coatings can be made, which are free of pinholes [5]. Although, this technology is in its infancy, the prospects are good.

2.3 TEMPERATURE SENSORS (AND ACTUATORS)

Temperature detection can easily be performed with the help of thermo-resistive elements. We do not restrict ourselves to materials that are compatible with the silicon IC-process. The fluid and electronic systems should be combined in a "hybrid" system. Smart fluid systems in the sense of, say, integrated sensors are out of reach. Smart components, used in a system like the MESA-MFS are conceivable. However, one should consider the necessity and the economics of such components in an overall system, where mounting, bonding, connecting, etc. is necessary anyway.

Temperature can also be sensed using thermo-electric effects in doped silicon structures. Since this transduction effect is reversible, the use of Peltier actuators is worth to be considered in processes that must be well controlled with respect to temperature.

3. Sieves

A sieve (as depicted in fig.6) is necessary as an obstruction for dirt and possibly for gas bubbles in a liquid. The latter function might be useful in filling up a system. A gas bubble separator is well conceivable, and it seems possible to design bubble outflow parts. Sieves can be made rather easily in silicon technology. The pore holes can be designed in diameter and depth, using dry chemical etching techniques. In a system such sieves can be designed to function at several places, combined with a channel system to remove dirt or bubbles. One has to look to such components as in electronics. If the production and mounting of such parts is cheap, one can even design with some "overkill" with a very limited increase in cost, while the system integrity increases significantly.

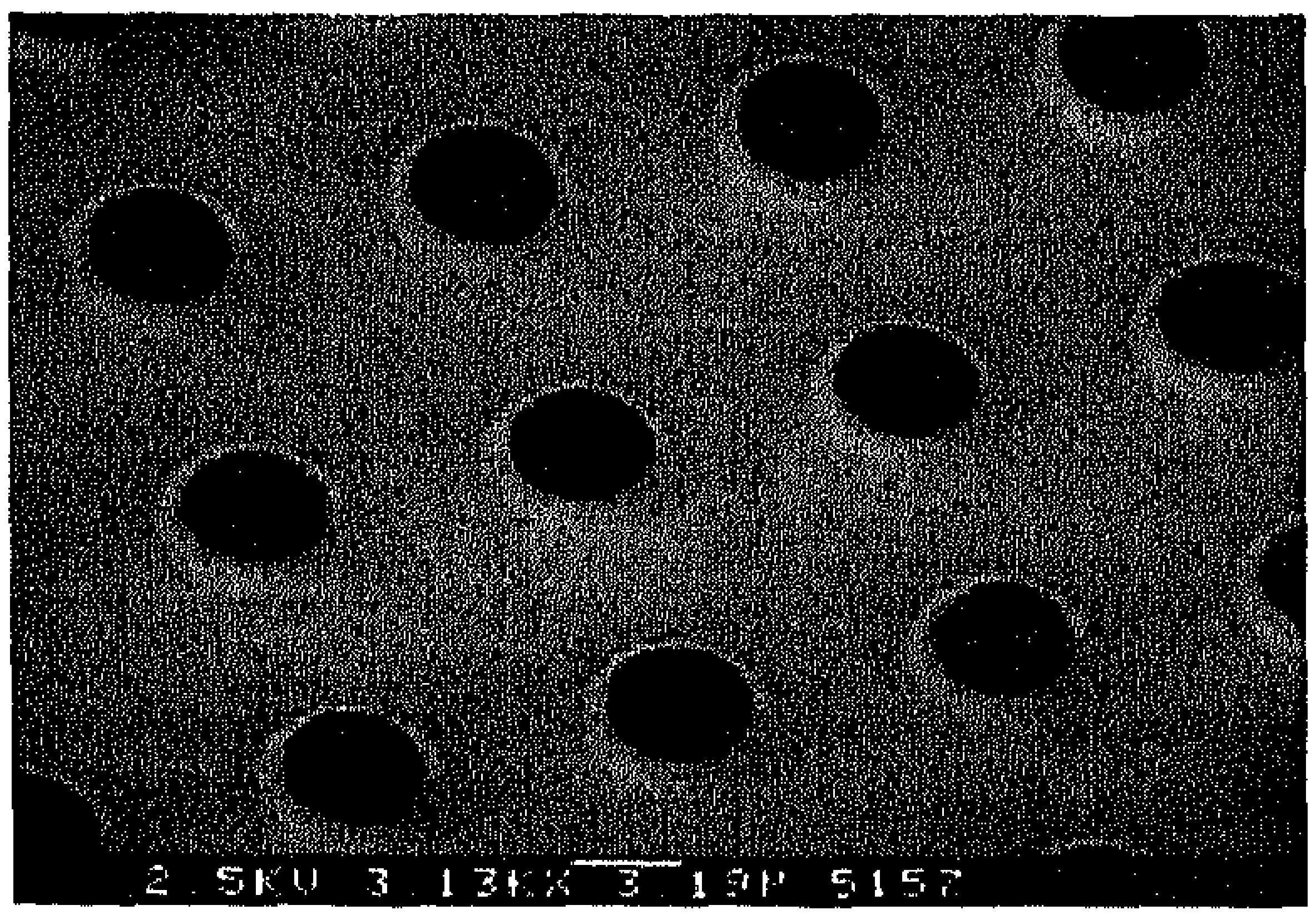


Figure 6. Electron micrograph of a part of a microsieve with holes of 5 µm [6].

4. Mixers/reaction chambers

The problem with mixers/reaction chambers is, that the down scaling of the fluidic process lead to Reynolds numbers which are much smaller than the values that are characteristic for the onset of turbulence [7]. Therefore it is not possible to increase the contact area of fluids to be mixed by "stirring". One is forced to look for solutions that increase the contact area in laminar flow situation. An elegant proposal for such a mixer/reaction chamber is from Miyake *et al.* [8], developed at our Institute. One of the fluids is pressed through a matrix of tiny holes perpendicular to the flow direction of the second fluid. The bulbs of the first fluid as they arise out of the holes into the second fluid leads to a large increase of the contact area and consequently of the diffusion process (see figure 7). As far as we know there are no other miniaturised mixers/reaction chambers described in the literature.

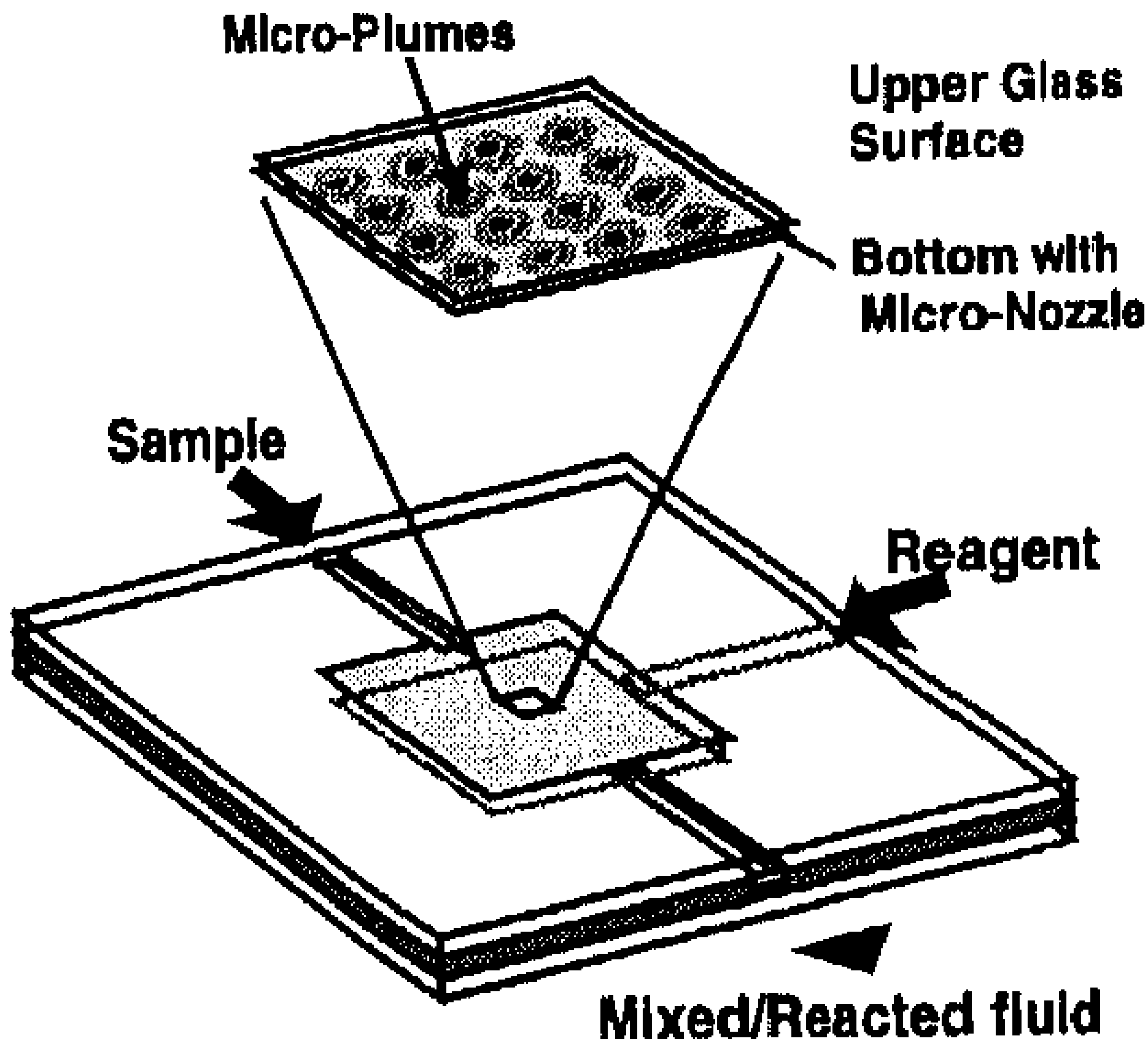


Figure 7. Basic principle of the micro-mixer

If one thinks of a straight forward mixer, being a channel with two sheet flows at the entrance, diffusion takes about 1 second to mix two 10 micron thick sheets [8]. So one can reduce the channel length of such a straight forward mixer by having a low velocity V. Here again the relevance of the velocity V over the volume flow F shows up.

5. Valves

Passive valves open and close as a consequence of the pressure distribution of the fluid at both side of the valve. They function as safety guards or as checker valves in a pump (next section). Active valves are controlled by signals from the system and therefore need an actuator to deliver the work for opening or closing the valve or put it in a correct position in a flow controller. Apart from the action, the actuators must be designed such, that they can maintain the valve position in a steady state. There are many valve designs, most of them are of the type that moves a membrane onto a valve seat (figure 8).

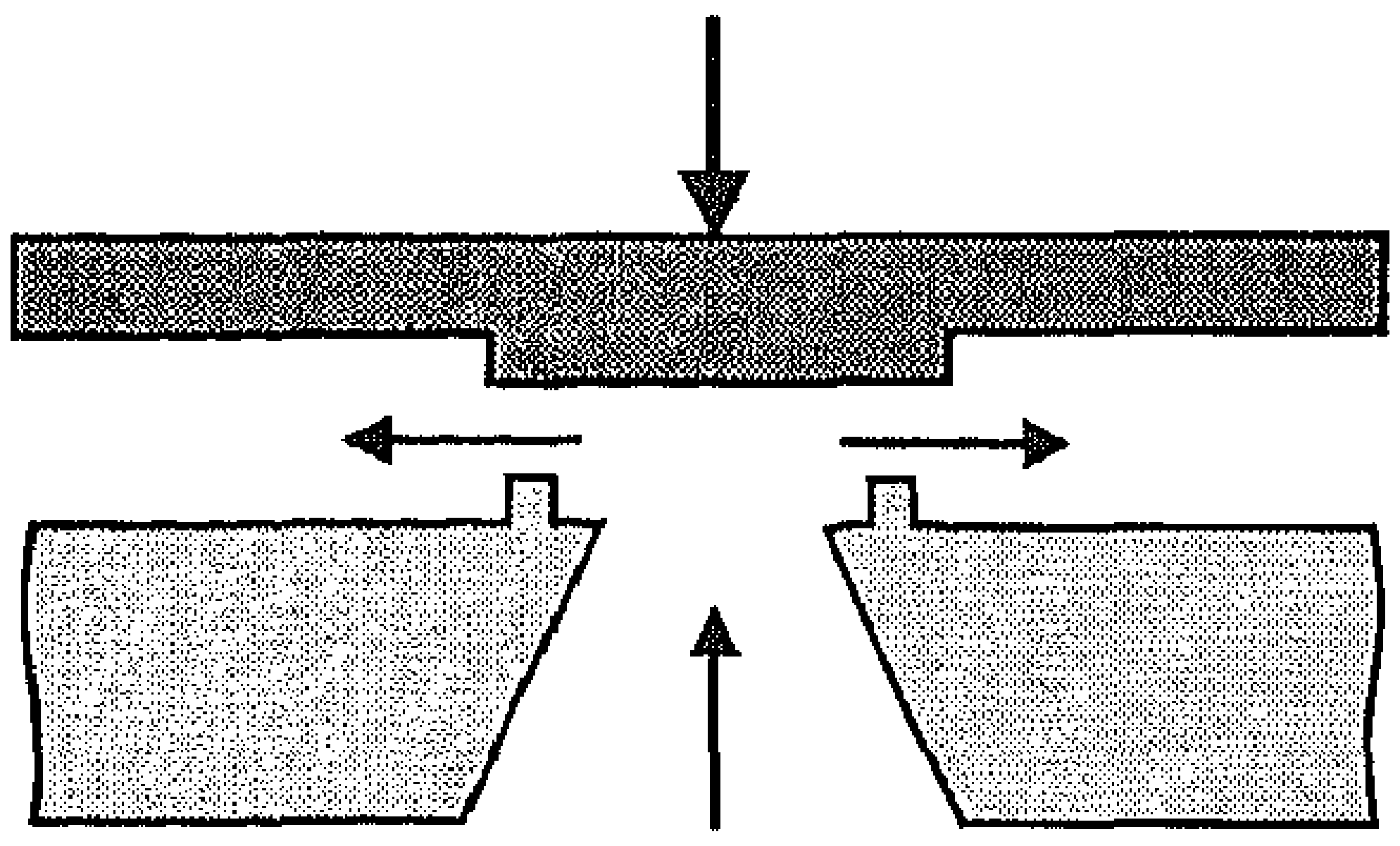


Figure 8. Valve with restriction perpendicular to fluid flow.

The favourite actuators to move the membrane are piezo stacks [9], thermal bimorphs [10], and thermal expansion chambers. The latter may comprise a liquid or gas, but the best solution is to have a medium that is in the phase change region, e.g. a liquid gas mixture. The great advantage is, that very high pressures can be reached with moderate power and that the temperature stays within a restricted range. A possible disadvantage may be the wafer scale filling of the pressure chambers. Anyway, the most successful commercial valve is based on the latter principle [7]. An analysis of its working principle has been published by Ji *et al.* [11].

Very important for a valve is, that in a closed position the valve must withstand the possible fluid pressure in the system, without leakage. Since a normally open valve must be active in this situation, one must analyse the open/closed ratio under operation in order to make a choice for a normally open or normally closed valve. It is also possible to design a valve with pressure compensation, such that the over pressure to be controlled is reduced [12] or even be used to enhance the valve position [10].

Controlled valves can be used in analog mode, e.g. as pressure reducers. In any flow analysis system, controlled pressures are needed to keep things moving. It fully depends on the application whether compressors, pumps and/or injectors are in the system or outside. In the latter case, on board controlled valves can do the job to create the desired flow pattern in the system. Gas bubbles must be prevented in a micro liquid flow system, because of their blocking effect. However one can also make use of gas bubbles in an open/close valve, and even as an actuator principle for pumping, as shown by Lin et al. [13].

6.Pumps

Many proposals and feasibility studies for micro pumps can be found in the literature. The most important micro pump type is the miniaturized checker valve pump (figure 9).

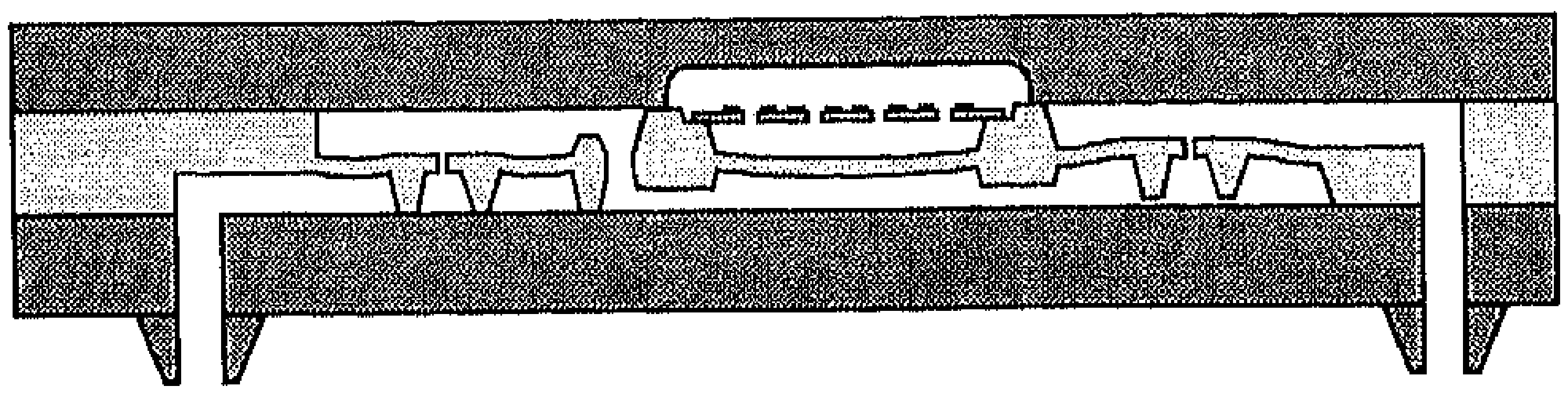


Figure 9. Cross section of a thermopneumatic checker valve pump [14].

It depends mainly on the actuator, which is the central element in the pump, what counter pressures can be reached. In the literature "low pressure" pumps are presented [15], but the desired pressures can be upgraded by using the phase change type of actuator, the thermal bubble jet principle [16], or even by making use of a pneumatic actuator driven by pressures generated in macro systems outside the micro system. The latter solution might seem odd, but it completely depends on the requirements of the application, how the system is designed. If, for instance, the micro system is designed for minimal use of liquids, minimal production of waste and a high throughput, but can remain on the "bench", there is no reason to exclude pneumatic actuation generated in a macro device on the same bench.

So, this again is an example of an application, which shows how difficult it is to talk in general terms. One should never overlook available solutions from the macro world, or the world of precision engineering, to design the best performing system for the application one has in mind.

A point with regard to the checker valve pumps (and also other pump types [17]) is the "heart beat". Indeed the pump in the system can be seen as the heart, but it may be required that other core elements must receive a flow with only a restricted ripple. Two pumps, side by side, pumping out of phase partly solve this, but it might be necessary to have a material buffer and a constriction to level of the ripple analogous as is done in electronics. Of course the introduction of a buffer suffers from the disadvantage that in a single analysis action the whole buffer must be filled with the liquid, which might be far more than necessary for the analysis itself. Again a consideration of possibilities starting with the application requirements is necessary.

A non checker valve type worth mentioning is the diffuser/nozzle pump [17] based on asymmetry of the pump structure. This pump is not free from backwards leakage, which can be solved by putting an open/close valve in series. Finally we want to mention the electro hydrostatic pump mechanism [18], which can produce a steady flow because it generates "body forces" on the liquid. However this pump requires high voltage and can be used only for a restricted kind of liquids.

It is a matter of course that a pump must always be accompanied by a flow sensor to have a well described component: an active micro flow controller or dosing system.

7. Design of Micro Fluidic Systems

An important design tool for micro fluidic systems is the CAMAS- or the older TUTSIM-design tool based on the use of bondgraphs. Unfortunately bondgraph modelling is not very popular and ill understood. Zengerle *et al.* for example, state that "more general design rules are needed", while bond graph modelling factually reflects physical systems in the most general way thinkable. It is based on energetic and entropic principles and cover physical processes in any physical domain. Introduced in 1961 by Paynter [19] a thorough background in physical systems theory has been worked out by Breedveld [20]. However, there is a lack of modern introductions, because the use of bondgraphs require a mental adaptation that is experienced by many persons as "user unfriendly". Nevertheless there is the review paper of Van Dixhoorn [21] and the CAMAS-introduction of Broenink [22], that might be of any help.

The elegance of bondgraph modelling is that it connects physical phenomena from whatever physical domain and that it can be used in a hierarchical way: supersystems, systems, subsystems. To give an idea of the latter, see figure 10, taken from [23] .

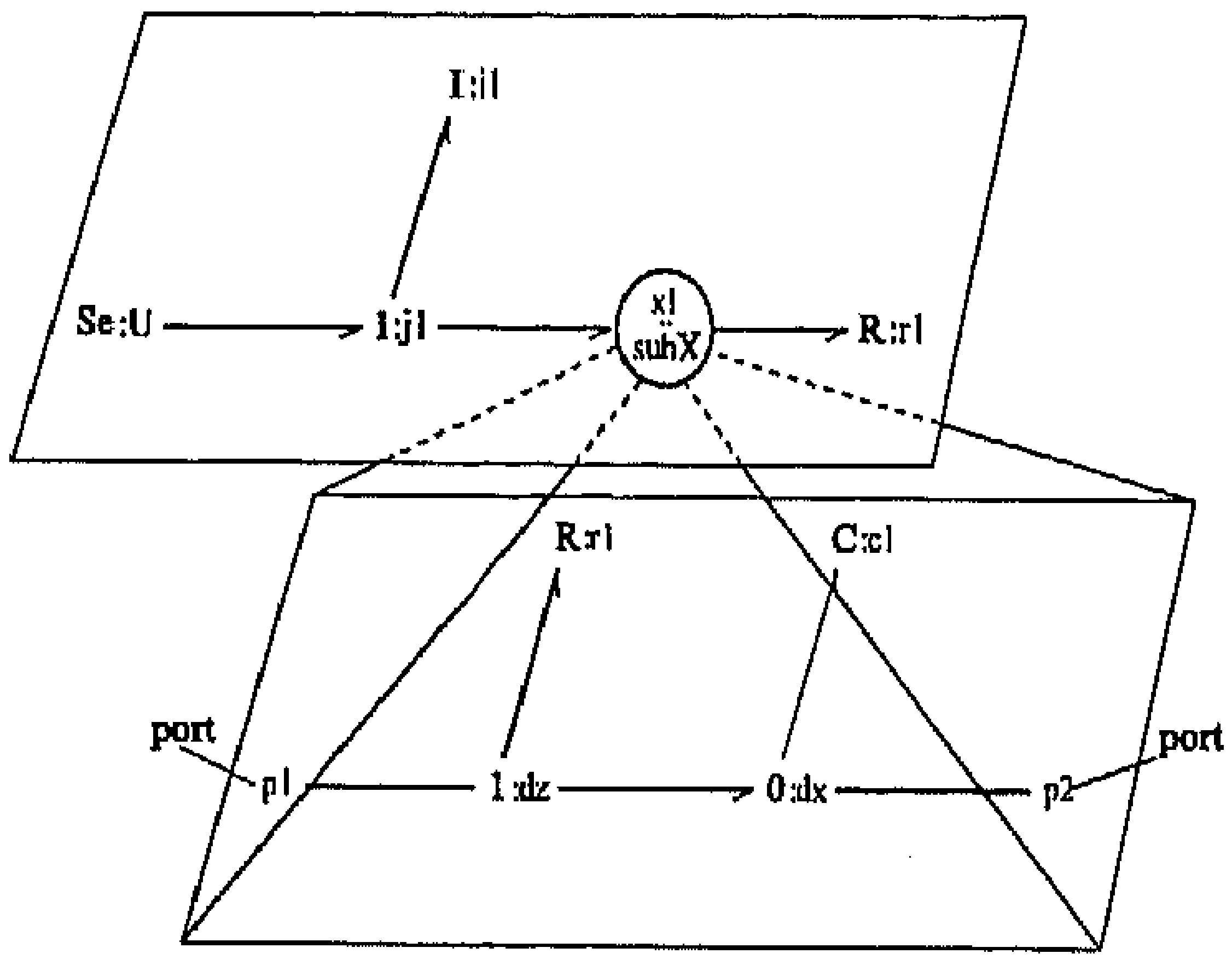


Figure 10. Bondgraph modelling of system with subsystem

For example, the subsystem might be a pump, which can be modelled with the help of bondgraphs and easily be introduced in the system as a whole, also modelled with bondgraphs. Subsystems, modelled by means of other computational techniques, can also be introduced by means of and adaptation of the subsystem's behaviour in terms of the input/output relations at the ports in the total system's bondgraph.

Van der Pol, in his thesis work [14] has shown, how the thermal, the pneumatic and the hydraulic subsystems, present in a thermally driven pump can be modelled. So a subsystem does not need to be a part that can be separated geometrically, but also a "part" that is contains the relations in a physical domain, e.g. mechanical or thermal.

Future work will show the advantage of bondgraph modelling and simulation and we expect CAMAS to be an important tool in designing micro fluid systems.

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