Modular Concept for Miniature Chemical Systems

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Summary

Miniaturised chemical systems comprise components for fluid manipulation (channels, pumps, valves etc.), (bio)chemical reaction and analysis. We propose a generic concept consisting of a so-called Mixed Circuit Board (MCB) containing both the fluidic channels and electrical circuitry as well as the silicon-based modules. The modules have a standardized connection to the MCB both for fluids as for electrical signals. In- and output modules have connections with capillaries used for liquid chromatography, ensuring the compatibility with this separation technique. The MCB itself consists either of glass-bonded silicon with anisotropically etched channels, but can ultimately be made as plastic component with use of moulding techniques. A number of system components such as a micropump, a capillary connector, a flow sensor, a micromixer (reactor) and a microfilter will be presented. An example of an electrochemical microreactor (microtitrator) will be given, and it will be shown how incorporation of this microreactor in a Micro Total Analysis System (μTAS) improves its performance. Finally a potential future realisation of a more complicated system, a parallel multisystem for chemical processparameter optimisation, will be evaluated.

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Zusammenfassung

Miniaturisierte chemische Systeme bestehen aus verschiedenartigen Komponenten zur 'Kontrolle' von Flüssigkeiten (Kanäle, Pumpen, Ventile, etc.), zur Erzeugung von (bio)chemischen Reaktionen und zur Analyse. Es wird ein allgemeines Konzept für ein derartiges System vorgeschlagen, das aus einem sogenannten Mixed Circuit Board (MCB) besteht, und welches sowohl die eigentlichen Flußkanäle und die elektrische Schaltung als auch die auf Siliziumtechnologie basierenden Module beinhaltet. Diese Module besitzen eine standardisierte Verbindung zum MCB, und zwar sowohl für die Flüssigkeiten als auch für die elektrischen Signale. Die Ein- und Ausgangsmodule weisen Verbindungen zu Kapillaren auf, die zur Flüssigkeitschromatographie verwendet werden, und stellen damit die Kompatibilität zu dieser Trenntechnik sicher. Für das MCB selbst verwendet man üblicherweise glasgebondetes Silizium mit anisotrop geätzten Kanälen, es kann letztendlich allerdings auch aus Plastikkomponenten bestehen, die mittels spezieller Formtechniken erzeugt werden. Ein Teil dieser Systemkomponenten, wie zum Beispiel Mikropumpe, Kapillarverbindung, Flussensor, Mikroreaktor und Mikrofilter, werden vorgestellt. Weiterhin wird ein Beispiel eines elektrochemischen Mikroreaktors (Mikrotitrator) präsentiert, und es wird gezeigt, wie die Einbindung dieses Mikroreaktors in ein 'Totales-Mikro-Analyse-System' (Micro Total Analysis System = μTAS) die Funktionsweise des gesamten Systems verbessert. Zuletzt wird eine mögliche zukünftige Realisierung eines komplizierteren und komplexeren Systems - ein parallel arbeitendes Mehr-Komponenten-System zur Optimierung chemischer Prozeßparameter - diskutiert.

1. Introduction

During the past few decades a large variety of chemical microsensors has been developed. A large amount of sensor principles such as optical, electrochemical, mass-sensitive and calorimetric have been developed [1]. However, few of these sensors have made the way to the market. One of the main reasons for this was the inherent limitation of chemical sensor performance caused by sensor drift and loss of selectivity and sensitivity. For this reason, actuators were added which enabled calibration of the sensor. Thanks to revolutionary developments in silicon microtechnology, in the last decade many so-called fluid-handling elements have been developed. Using these elements, complete micro-analysis systems could be built. One of the problems encountered with such systems, however, is that due to their high complexity it is virtually impossible to develop and fabricate all necessary components alone. For this reason we have developed a generic hybrid concept, a "Micro Fluidic System" (MFS) enabling the composition of a complex analysis system by integrating different components on one "motherboard" [2].

A logical further step in the realization of microsystems is the addition of some sort of micro reaction chamber to the system. Such a chamber may be used to simply mix two chemical reagents [3], or carry out a thermally induced chemical reaction in liquid [4] or gas phase (using a catalyst) [5]. The whole process of integration is illustrated in fig. 1.

In this paper the MFS concept, as well as several components used in it will be described. Besides, an example of a electrochemical sensor-actuator system (microtitrator) will be given. Because of some shortcomings of this system, it will be shown how incorporation of this microreactor in a Micro

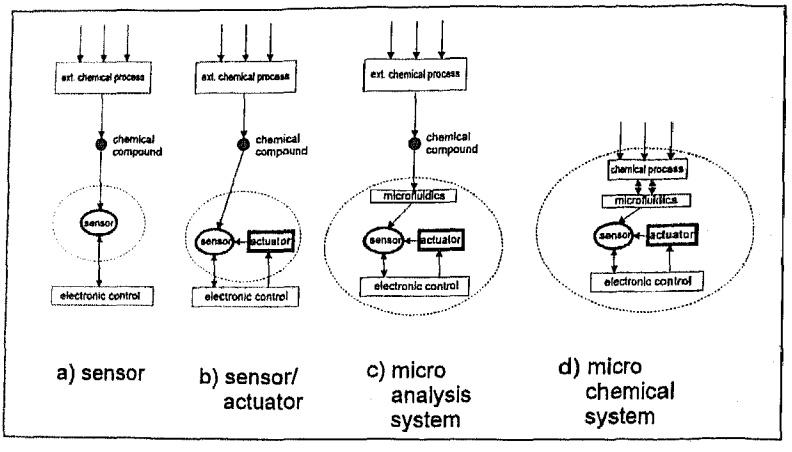


Fig. 1 Process of integration of sensors, actuators, fluidics and reactors into a micro chemical system.

Total Analysis System (μTAS) improves its performance. Finally some potential future realisations of more complicated systems, such as a parallel multisystem for chemical process-parameter optimisation, will be evaluated.

2. Micro Fluid System (MFS) Concept

For the integration of components for fluid-handling into a system, several approaches have been proposed. Van der Schoot et al. [6] proposed a vertical, stackwise arrangement of components which has the advantage of efficient use of surface area but the disadvantage of being rather inflexible. An alternative was presented by Fiehn et al. [7], who presented a Fluidic ISFET-Microsystem (FIM) based on a planar integrated system. The main disadvantage of this system is that a whole processed glass-bonded silicon wafer is used as system substrate. Recently, an alternative was presented in

which the components are at least partly, reversibly mounted in a way perpendicular to the substrate [8]. In the latter system, which uses a silicon sealing for hermeticity, the advantage is that each component can be replaced. The disadvantage is that the fabrication of the system is not easily automated.

The Micro Fluidic System (MFS) we propose is composed of a so-called Mixed Circuit Board (MCB) containing the fluid channels as well as the electronic circuitry in combination with the silicon-based fluidic components (modules). These modules have a standardised connection to the planar MCB both for fluids and electrical signals. The MCB consists of a glass-bonded silicon backplate in a first stage, whereas in the second stage (laminated) plastics are used (see fig.2). In fig. 3 an example is given of how the electrical and mechanical layout of such a microanalysis system looks like.

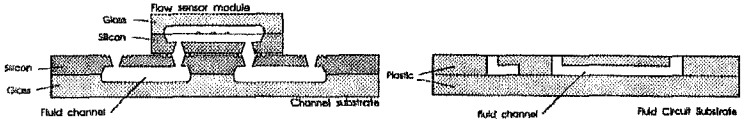


Fig. 2 Flow sensor module on Si-glass bonded substrate (left) and plastic Mixed Circuit Board (right).

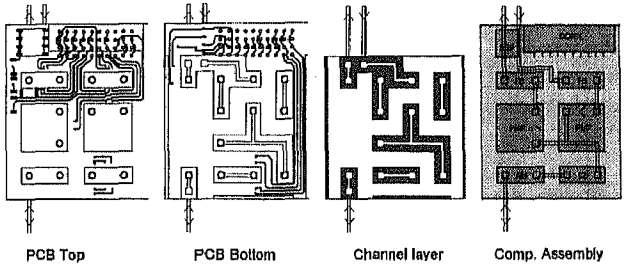
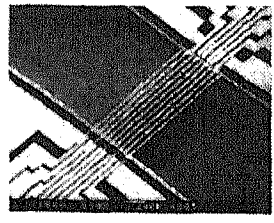
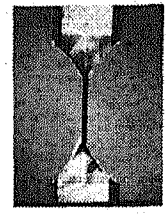


Fig. 3 Schematics of floorplan with mixed electrical and fluid connections.

For the realisation of Micro Fluidic Systems (MFS) a wide variety of components is needed. Many of them, like pumps, flow-sensors and filters, were already developed at MESA [9]. For integration in the MFS new designs have been made of a number of components that made them compatible with mentioned concept. In Fig. 4 examples are shown of a flow sensor, a resistor, a filter/mixer module, a micropump, and a microvalve specially designed for integration in MFS.

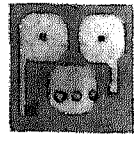


Beam type flow sensor

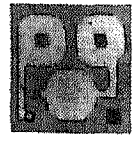


Resistor

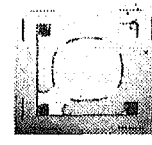
Filter/mixer module [2]



Pump (top)



Pump(bottom)



Pressure Controlled Valve (top-bottom)

Fig. 4 Photographs of a number of different components for the Micro Fluidic System (MFS).

3. Coulometric Microtitrator

In earlier studies, the development of a coulometric acid/base titrator has been described [12,13]. This structure consists of an electrochemical actuator combined with an ISFET pH-sensor (see fig. 5).

With this sensor-actuator device fast titrations can be carried out, and the titration time t_{end} is directly related to the acid/base concentration to be determined via the formula:

$$\frac{\partial\sqrt{t_{end}}}{\partial C_{acid}} = \frac{F\sqrt{\pi D_{acid}}}{2j_c}, \qquad (1)$$

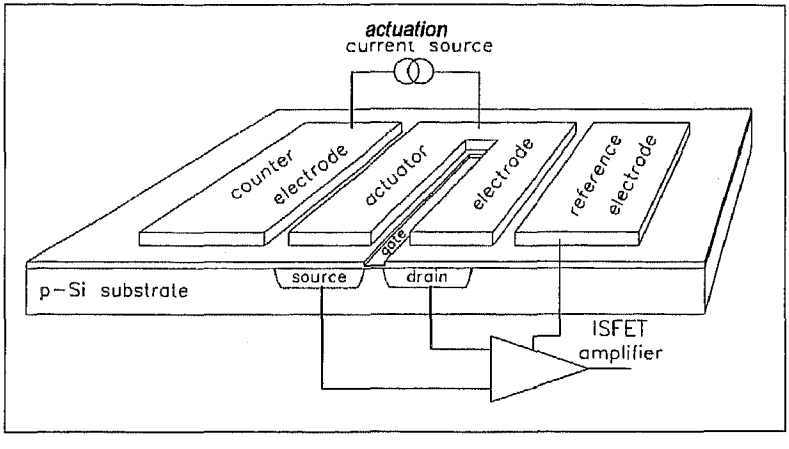


Fig. 5 Basic elements of the coulometric sensor-actuator device.

with j_c is the cathodic current density through the actuator, C_{acid} and D_{acid} respectively the concentration and diffusion coefficient of the acid and F is Faraday constant. A typical plot of the square root of t_{end} *vs.* acid concentrations of acetic and nitric acid is shown in figure 6.

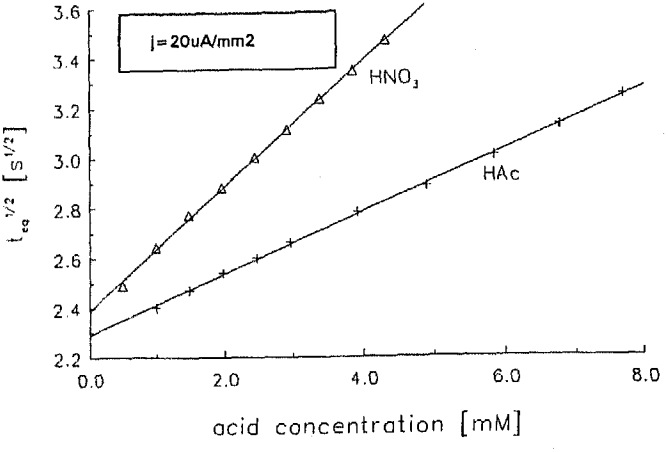


Fig. 6 Square root of t_{end} as a function of both HAc and HNO_3 concentrations.

In practice, it appears that the coulometric actuator device, if operated as such, shows some disadvantages. First of all, there is no linear relation between titration end point and the required concentration. Secondly, the proper functioning of the device relies on the presence of only one type of mass transport: diffusion. Effects of migration may strongly influence the measurement, and to overcome this an excess concentration of supporting electrolyte is needed. Finally, as shown in fig. 6, the operational range is limited to a maximum of approximately 10 mM, caused by limitations in the current density. This upper limit turns out to be problematic with respect to the much higher total acid concentrations in several food products, such as fruit juice or wine (50 to 150 mM). The problems mentioned above can be overcome by incorporation of the microtitrator in a Micro Total Analysis System (μTAS).

As a start, let us consider the sensor-actuator device in differential mode to be placed in a small-volume reaction chamber, as schematically shown in figure 7. The height h of the reaction chamber is chosen small (typically 25 μm) with respect to the mean diffusion layer thickness after a few seconds of titrant generation (typically 100 to 500 μm). In addition, the actuator area A is chosen large (e.g. 1 to 5 mm^2) with respect to the mean diffusion layer thickness. Consequently, a homogeneous coulometric titration can be considered to take place in the volume formed by A · h. The slope of the curve, resulting from a series of measurements in different acid concentrations, C_{acid}, can now be expressed as

$$\frac{\partial t_{end}}{\partial C_{acid}} = \frac{FAh}{I_c} \qquad (2)$$

with I_c is the current through the actuator. When comparing (1) with (2), it is clear that in the latter equation the diffusion coefficient is absent: regardless of any difference in the diffusion coefficient, the time to reach the end point t_{end} in the titration curve will, for a constant current I_c, depend only on the acid concentration (expressed in its corresponding normality). This is an important advantage over the former operation principle: that of free diffusion. It is also clear from (2) that the relation between the acid concentration and t_{end} is linear, which may simplify subsequent signal processing.

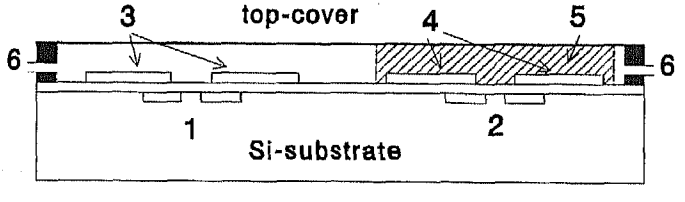


Fig.7 Reaction chamber with (1) reference ISFET, (2) indicator ISFET, (3) pseudo-ref. electrode, (4) actuator, (5) titration volume and (6) spacer with inlet and outlet.

Because lateral mass transport still would influence the measuring result, convection must be avoided, which is very easy in the small-volume reaction chamber after the valve controlling the inlet flow is closed: the sample in the reaction chamber will be at rest immediately.

Considering migration, the second undesirable means of mass transport, another advantage of μTAS comes in view: the possibility to add supporting electrolyte. Both the proper control of the titrant-generating actuator current and the avoidance of migration requires a lower limit for the ion strength of the sample. With μTAS, a very small volume of a high concentration of neutral supporting electrolyte can be added and mixed with the analyte in a mixing chamber, thereby hardly changing the concentration of the acid. Finally, the injection and mixing of moderate volumes of supporting electrolyte can be used to deliberately dilute the sample in order to be able to measure high acid (or base) concentrations, e.g. in fruit juices.

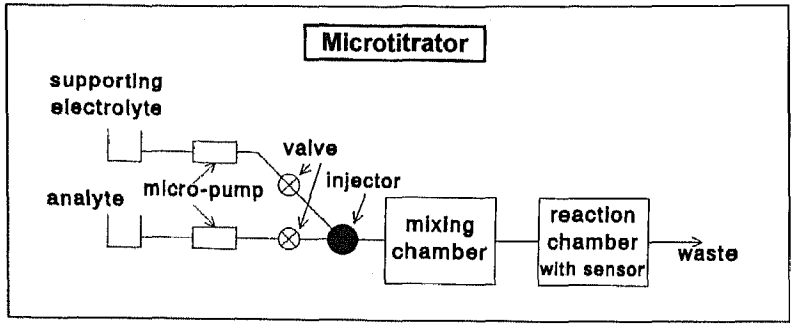


Fig. 8 The proposed μTAS for improved coulometric sensor-actuator performance.

The μTAS thus proposed, including subsystems, is schematically shown in figure 8. In reality the mixing and reaction chamber might be one chamber only. Also, the micro-pump itself might function as a valve.

4. Micro Chemical Reactor Array

Monocristalline silicon is particularly suited for the realization of anisotropically etched micro chambers or reactors, closed at one side by a thin membrane. A thin film heater can be deposited on this membrane enabling the most straightforward way of heating the reactor volume, both for liquids as gases [14,15]. Furthermore the microreactor is easily combined with a thin film catalyst (Pt) such as used for catalytic gas sensors [5] and can be covered by a glass cover, allowing optical excitation. Finally, the Pyrex-silicon sealing is tight enough to make experiments under high pressure (up to 200 bar [16]) possible (see fig. 9).

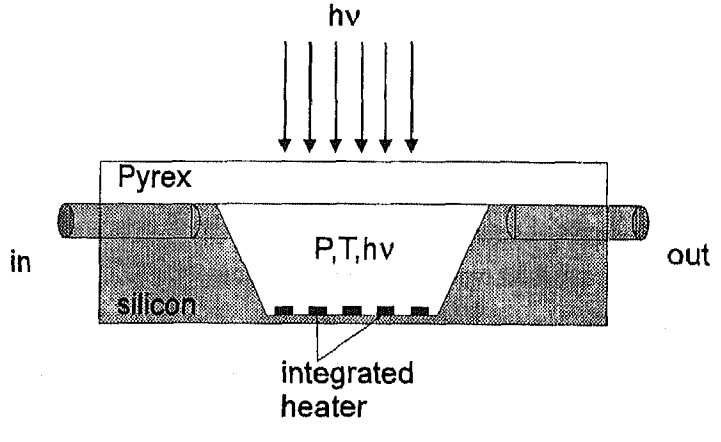


Fig. 9 Microfabricated reactor with controlled pressure, temperature and illumination.

Typical dimensions of the above-mentioned microreactors are in the order of a few square millimeters. This allows the arrangement of large numbers of them in coupled arrays. The small size of the microreactor offers a number of advantages: negligible amounts of chemical waste, no explosion danger, and fast control of temperature and pressure. Potential applications are found in the filed of reaction kinetics and reaction parameter optimization for instance in organic synthesis e.g. in pharmaceutical industry (see fig. 10).

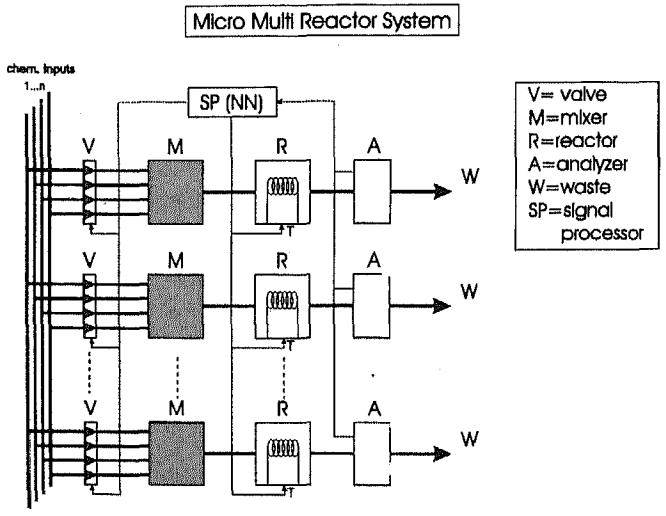


Fig. 10 Example of a microreactor array with analysis units coupled with signal processing unit for reaction parameter optimization.

In this system the valves V are controlled in such a way that the required reaction product is obtained with maximum yield. The parallel configuration of many reactors helps to increase the speed of the reaction optimization. Alternatively, products of the reactions may be fed back to the inputs of the

valve units. In this case, the dynamic behavior of coupled chemical reactions may be studied. The proposed setup can be used for both gas and liquid systems.

5. Conclusion

A modular system concept for fluid handling (Micro Fluidic System, MFS) has been proposed for the realization of micro total analysis systems and micro chemical systems. MFS enables the use of standard components or modules to be integrated on a planar base plate that contains fluid channels as well as electronic circuitry. Through the standardization the exchange of different components from different suppliers is stimulated. An example of a microreactor in the form of a microtitrator is presented and it is illustrated how incorporation of this microreactor in a micro total analysis system improves it performance and avoids some of it disadvantages. Finally an example is given of a microreactor array system for optimization of chemical reactions.

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