Progress and profit through micro technologies.
Commercial applications of MEMS / MOEMS

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Abstract

Micro technology deals with miniaturization and integration in all areas of technology outside of microelectronics like micro mechanics, micro optics, micro acoustics, micro fluid technology, micro reaction technology and further disciplines which are focused on technical components and systems with characteristic dimensions in the micrometer range. Within a period of about ten years a multi-billion dollar market has been set up with many products for daily life. The growth rate of the market of micro technology will remain on a high level for the years to come. Mega trends resulting from fundamental human wishes for health, information, mobility and sustainable development are creating a further growing basis for micro technical products. A broad spectrum of production processes and materials has been developed to meet the requirements of a strongly diversified range of applications. For the development of new components and systems the importance of software tools for simulation of functional properties, production processes and comprehensive optimization is growing rapidly. Micro devices are meanwhile used extensively in information, automotive, and medical technologies. In addition, micro technology is generating a completely novel basis for chemical engineering, life sciences, industrial automation and optical communication, to mention only a few disciplines where future innovation will be dominated by miniaturization.

Keywords: Micro technology market, micro fabrication, mathematical modelling, micro devices, medical technology, life sciences, information technology, mobility, micro reactors

1. A technology with an enormous leverage

At the beginning of a century and the more of a millennium there always arises the question about new technological developments, which will fundamentally influence life in the future. Evidently, a rather large number of technologies will do that like microelectronics, information technology, biotechnology, genetic engineering, proteomics, power generation by means of solar farms, fuel cells or eventually nuclear fusion and there are many more which could be added to this list. A particularly important discipline will be a technology usually characterized by acronyms like MEMS (micro electro mechanical systems), MOEMS (micro opto mechanical systems), or MST (micro system technology), which we will simply call micro technology in this article. Its effect on technological progress has been tremendous and will increase further. Micro technology will be a key factor of innovation in the years to come [1,2].

Micro technology is an outstanding strategy for success. It uses the same principles and concepts as microelectronics, i.e. consistent miniaturization and comprehensive integration. But, in micro technology this strategy applies to mechanical, acoustic, optical, magnetic, thermal, chemical or biomechanical components and systems. Micro technical elements take up less space, require less energy and material, they are predestined for cost-saving batch production in the same way as microelectronic chips due to their smallness. And in the same way as for highly integrated semiconductor circuits, the following also applies: Micro technical products will be constantly more powerful due to integration of ever more functional elements into systems.

Within a period of a little more than a decade, micro technology has become a multi-billion market [3]. Products with micro technical functional elements have made their way into everyday life: in the form of laser heads in CD and DVD units for entertainment, as read-write heads in magnetic hard disks for information, as acoustic frequency filters in cellular phones for communication, and also in heart pacemakers or hearing aids for our health [3]. But this is not all, by a long way. A modern car uses around 30 micro technical products to cover driving comfort, personal protection, engine management, and road performance [3,4]. And micro technology is moving forward in the most important interface
between the human being and the digital world, the monitors or displays [5]. Flat panel displays are micro technical products, whether one considers thin film transistor liquid crystal displays, plasma displays, organic light emitting diodes (OLEDs), or other flat panel systems. Micro technology is in 3D cyber-glasses and also in large-scale video projection with digital mirror devices, in which there are more than a million controllable micro mirrors squeezed onto a chip that is just a few square centimeters in size. Pharmaceutical companies and biotechnical startups are investing in micro technology in order to save on materials, time and expensive substances by using miniaturized devices for high throughput screening; we are standing on the threshold of a breathtaking development [6].

The economic and technical leverage of micro technology is enormous. The annual turnover for micro technical products is already more than 60 billion US $ (including CD and DVD micro devices and flat panels) as of today (2001) and products with a sales value that is many times greater are only possible or competitive today due to micro technology. The leverage effect obviously means that micro technology is affecting volumes of some hundred billion US $ per year. We have the same situation in micro technology as for microelectronics about 20 to 30 years ago. Micro technology is one of the outstanding key technologies on the threshold of the 21st century. It will create wealth and, in particular, hundreds of thousands of jobs for scientists, engineers and many other professions.

2. Mega trends for micro technology

It is absolutely impossible to forecast seriously what the market volume of micro technology will be in the year 2020. However, for the next five years a strongly increasing number of micro devices will be needed by many companies to remain competitive by realizing novel products with micro technical components or systems. This demand will be met by more and more enterprises and, accordingly, a growth rate in global sales of about 20% or even much more in some areas can be anticipated for this period.

Nevertheless, a general conclusion concerning the next ten years can be drawn when regarding fundamental human wishes and the consequences for technological progress. In the case of micro technology these are in particular the wishes and desire for health, information and communication, entertainment, mobility and sustainable development, which push the corresponding mega trends of commerce and technology. Micro technology in the health area ranges from intelligent implants to minimum invasive therapy and micro devices for drug development by high throughput screening. Typical examples dealing with micro technology in information, communication and entertainment like cellular phones or compact disks have been mentioned already in the preceding section. Mobility is improved by weight reduction due to miniaturization and better performance due to integration of more and more functional elements. Concerning sustainable development, micro reaction technology is to be regarded as a leap into a new era of chemistry with higher efficiency, less waste and environment-friendly distributed production in smaller plants.

3. Three-dimensional micro fabrication

In order to profit from the huge business opportunities offered by micro technology, a considerable number of micro fabrication methods have to be applied. Basic prerequisites are, of course, small dimensions, precision and, in particular, the possibility to realize complex three-dimensional structures. Three-dimensionality is of fundamental importance in micro technology since, in contrast to microelectronics, micro mechanics and micro fluidics need on principle high aspect ratio structures for many applications. Because of the wide variety of functional properties of micro products, a broad spectrum of materials is required comprising metals and metal alloys, plastics, glass, ceramic materials, semiconductor materials like silicon and many auxiliary materials for intermediate process steps like resists or solvents as well as for connecting, sealing, surface treatment, protection etc. Besides such basic aspects concerning materials and shape of micro devices, costs play a major role in the selection of a micro fabrication process. In this respect, the number of pieces and the precision, which is really required, as well as aspects like availability, manufacturing experience etc. have to be considered.

Some ten years ago, the LIGA method was regarded to be the only technology to produce ultra precise micro structures with extreme aspect ratio from a wide variety of materials [7]. It is based on a combination of deep lithography, electroforming and moulding processes. In the first step of the manufacturing sequence, a pattern from a mask is transferred into a thick resist layer on an electrically conductive substrate. Ultra precise micro structures with extreme
aspect ratio can be generated by deep X-ray lithography but, using special epoxy resists like SU 8, favorable results are also achievable by means of UV lithography. In the second step, the three-dimensional structure generated by means of deep lithography is transferred into a complementary metallic structure by means of electroforming starting from the electrically conductive substrate. This metal structure may be the final product in some special cases. In general, however, it is used in a third step as a master tool for replication processes like injection moulding, casting or embossing for mass fabrication of micro structures. A wide variety of mould materials can be applied like organic polymers, pre-ceramic polymers, ceramic and metallic powders with organic binders for subsequent sintering etc. so that most material requirements can be favourably met except those requiring, mono crystalline semiconductor materials.

Wet etching processes are widely used to produce micro structures by means of transferring resist patterns into various materials. However, for most materials only isotropic etching processes exist so that, because of lateral under-etching of the resist pattern, only shallow micro channels or other shallow structures can be generated at the surface of a bulk material [8]. This restriction can be overcome by wet chemical anisotropic etching of mono crystalline materials, particularly silicon, utilizing the dependence of etching velocity on crystal orientation. This method has been widely applied in micro technology but, as a matter of fact, only a few basic geometries can be realized [8]. Besides anisotropic etching of mono-crystalline materials a further wet chemical etching process exists which uses a special type of photosensitive glass [9]. A wafer of such glass is irradiated through a mask with UV light and subsequently heated to a temperature between 800 and 900K. This results in a crystallization of the irradiated regions, which can be dissolved much faster in hydrofluoric acid than the non-irradiated parts.

Much more precision and freedom in design of microstructures is offered by anisotropic plasma etching methods where again silicon is the most important and proven material [8]. Usually, a mask pattern is transferred into a thin layer consisting of a material resistant against plasma etching on a silicon wafer. Subsequently silicon is etched by means of fluorine containing low-pressure plasma, which generates gaseous silicon compounds. The directed etching process is usually accompanied by lateral etching and, depending on the composition of the plasma, also a deposition process from the plasma where the walls oriented in parallel to the etching direction are covered with a plasma polymer resistant against the reactive plasma. By means of a multiple repetition of directed etching and side wall passivation structures with nearly vertical walls can be realized and, accordingly, extremely high aspect ratios are achievable for nearly any cross-sectional shape.

For a number of applications dealing for example with movable micro devices anisotropic plasma etching and isotropic wet chemical etching processes are combined in the so-called sacrificial layer technique. This technique utilizes layers of different materials where the microstructures are generated in one kind of layers by means of lithographic patterning and anisotropic plasma etching. The other layers serve the purpose to stabilize the microstructures during the etching process and are subsequently dissolved by means of a highly selective etchant so that movable microstructures are obtained.

In the past few years, an impressive progress was achieved in so-called mechanical micro machining utilizing technologies based on so-called ultra-precision machining. Complex three-dimensional microstructures have been generated with shape accuracies in the sub-micrometer range by means of milling, turning and grinding [10]. Using diamond tools, an excellent surface quality of a few nanometers rms is achievable for nonferrous materials and progress has also been made in machining stainless steel by using ultra fine grain hard metal tools and novel technologies like vibration cutting. Moreover, there are further mechanical methods for high volume production like punching and embossing, which have meanwhile been successfully applied in fabricating micro devices.

An interesting alternative to standard mechanical micro milling, turning, drilling and grinding methods is micro electro discharge machining (EDM) which is virtually unlimited in view of the geometrical shape of the work piece [11]. Material is removed in a discharge between the electrically conductive work piece and an electrode by small sparks in a dielectric fluid. Disadvantages of micro EDM are a relatively large surface roughness and limitations in miniaturization because of the finite size of the electrodes and the spark gap in the electrical discharge.

Micro fabrication by means of laser radiation covers a wide range of different methods [12]. On the one hand, these are processes where material is removed in an intense electromagnetic field by melting, evaporation, decomposition, photo
ablation or a combination of these phenomena. On the other hand, generating processes exist where structures are built up from liquid resins, laminated layers, or powders using e.g. photo chemically induced cross-linking of organic compounds in stereo lithography or powder solidification by laser sintering. Such processes are of major importance for rapid prototyping of microstructures and they can even be carried out in parallel for mass production [13]. In addition, welding by means of laser radiation is of major importance for connection and assembly of micro devices. There are no restrictions worth mentioning concerning materials in micro machining by laser radiation. Limitations rather exist to achieve critical dimensions below 10µm and low surface roughness.

Due to various inherent prerequisites of micro devices, like special topology, function or inevitable incompatibilities of process steps, hybrid design and construction become much more important than in microelectronics where monolithic integration is the fundamental basis for design and production. As a matter of fact, hybrid micro devices are bound to efficient assembly methods to get access to commercially attractive large volume markets, i. e. highly parallel micro assembly is of fundamental importance for cost reasons. In order to meet these requirements an assembly process has been developed which utilises special features of the LIGA technology. The basic element is a plate-shaped magazine with embedded and spatially separated microstructures whose positions and orientations are precisely fixed in the magazine [14]. A multitude of microstructures can be pushed out of the magazine in parallel to their respective mounting positions in the corresponding devices, which results in minimum expenditures for handling tools and inspection. Meanwhile, the process has been successfully applied for assembly of multi-stage micro gear systems.

Compared to microelectronics, the product diversity of micro technology is much higher since it comprises a multitude of different disciplines like micro mechanics, micro optics, micro acoustics, micro fluidic technology, chemical and biochemical microanalysis etc. Accordingly, the spectrum of manufacturing methods, assembly techniques and materials for micro technology is very broad and is by far not covered by the description given above where only the most important processes have been listed. In many cases, a combination of various technologies has to be applied for production. A tremendous progress in three-dimensional micro fabrication has been achieved in the past few years and there are no longer really serious restrictions concerning insufficient freedom of design or lack of materials to realize a prototype of a micro device. However, there are still many economic hurdles concerning the high expenditure and risk of product development and, in particular, to achieve sufficiently low production costs.

4. Mathematical modeling

In view of costs and speed in product development mathematical modeling comprising simulation and optimization will play a dominating role the future of micro technology [15]. This is due to the fact that the costs for making a prototype do not decrease but increase often dramatically when the characteristic dimensions of a device shrink. Consequently, an experimental procedure according to the principle of trial and error is not advisable in micro technology. Already in the first step of product development, simulation of the device function may help essentially to save costs since it allows to work out realistic specifications in regard of functional properties and the corresponding requirements concerning materials, dimensions, stability, tolerances, surface roughness etc. These specifications are then a reliable basis to select an appropriate manufacturing process and to extend the basis for assessment of risks in view of costs and technological performance by means of process simulation. The next step in product development aims at optimization using the data from simulation of functional properties as well as those from simulation of suitable manufacturing processes.

Compared to microelectronics, the software environment of micro technology is still in its infancy. This is evidently due to the lack of standardization, the extreme diversity of applications, the variety of production methods and also the fast development of micro technology. Nevertheless, the situation is changing rapidly and excellent software tools are meanwhile achievable commercially for special applications. Such software tools cover the areas of micro optics and integrated optics, electromagnetic and electrostatic phenomena, micro fluid dynamics including chemical reactions and transport phenomena like diffusion, viscosity and heat transfer, mechanical properties like stability or vibration and many more. In many cases, no special tools for simulation of micro devices are required since the essential phenomena and the corresponding properties of most micro devices can be satisfactorily described by means of continuum physics. However, difficulties arise when molecular effects and, in particular, coupled phenomena have to be taken into account which sometimes cannot be separated as simply as in the macroscopic world.
Software tools are also available for mathematical modeling of special micro fabrication processes like deep lithography, wet and plasma based dry etching processes, electroforming, micro molding, etc. CAD tools also exist on a relatively broad basis when standard mechanical design software can be used. However, the situation becomes difficult when design rules are required which are, of course, standard in microelectronic design but not in micro technology. Since the pressure concerning reduction of development time and production costs will increase further in the fast growing market of micro technology and the performance of the micro technical software tools is improving rapidly, only those will survive in science and industry who design, simulate and optimize processes and products of micro technology on a comprehensive basis by means of modern software tools.

In the following, a multitude of micro devices and product concepts will be discussed which utilize the micro fabrication technologies summarized above and, of course, a variety of further processes from semiconductor technologies and precision engineering.

5. Medical technology

The strategy of miniaturization and integration is becoming of outstanding importance for the health sector for cost reasons as well as in regard of fundamental improvements of performance. Micro devices are meanwhile applied for medical diagnosis, therapy and, in particular, for biochemical drug development. Cardiac pacemakers, vascular stents, hearing aids, cochlea implants or microelectrodes for nerve stimulation have to be mentioned which support the function of human organs much more effectively than former devices manufactured by means of standard macroscopic production methods. Instruments for minimum invasive diagnosis and therapy like micro endoscopes and micro catheter systems are small but powerful tools for surgeons and help to reduce time and pain of operations. Micro spectrometers are applied for colour measurement of skin as a diagnostic tool for non-invasive measurement of bilirubin. Dentists use micro spectrometers to determine precisely the colour of teeth for dental prosthesis. Micro acceleration sensors have been integrated in artificial knee joints with a dramatic improvement of mobility for the patients.

Current basic developments on even more advanced micro-technological health products aim at the replacement of complex organic functions or even total organs. Implantable pancreas, artificial kidneys, connecting systems for nerves and retina implants may be mentioned in this context. It is open when such developments will find their way from basic research to medical application or whether the progress in molecular biotechnology will make such developments unnecessary.

Extensive progress has also been made in drug delivery systems based on micro technology. A very promising device with a high market potential uses micro nozzles for generating respirable aerosols of drugs with a defined droplet size, which is optimal for absorption by the lung. Commercially available are also implantable devices with micro capillary circuits for controlled release of analgesics and cancer drugs. Other drug delivery systems will be equipped with programmable micro pumps for precise control of release.

There is no doubt that the desire for health provides an interesting basis for progress and profit in medical technology for companies, which are able to utilise the inherent advantages of micro technology. Attractive business opportunities exist in particular for small and medium sized enterprises co-operating simultaneously with medical doctors and micro fabrication experts.

6. Life sciences

An extremely high potential for progress and profit in the future health business will be provided by micro technology in the area of life sciences, i.e. in molecular biotechnology for medical diagnosis, therapy, and drug development. Micro devices were already used successfully in the human genome project and novel micro devices presently under development will reduce further time and costs for DNA sequencing. They will pave the way for pharmacogenomics to apply medicines specifically adapted or even directly designed for the patient according to his genetic disposition.

The basic idea behind these so-called labs on a chip is to integrate many micro components into the smallest possible space and to build up microsystems for biological and chemical analysis. Because of the small characteristic dimensions and the high precision achievable with modern micro fabrication methods such credit card sized labs on a chip will...
usually be equipped with a large number of analyzing units. These units are superior by extremely short measuring times which is a well known inherent advantage of miniaturized devices often demonstrated in e.g. electrophoresis or chromatography [16]. In general, labs on a chip are disposable devices since it would be technically very difficult to clean and reactivate them after use. For cost reasons, micromoulding with plastics is regarded to be the most appropriate production process, which, of course, has to be completed by, further process steps for realing a lab on a chip.

Meanwhile, R&D activities deal not only with genomics but also with proteomics with the aim to analyze the proteom, i.e. all proteins of a given type of cells at a given time. Thus not only the genome, that means the design basis for the expression of proteins will be accessible but also the result of the expression process that means the proteom. Proteins are separated in such devices by means of combined isoelectric focusing and electrophoresis in micro channels with a width of only 50 micrometers. Thus, proteom chips will replace large, unwieldy and expensive gel plates used for 2D gel electrophoresis and improve tremendously speed, validity and range of medical diagnosis by highly parallel analysis. Optical and biochemical methods of analysis which aim at single molecule detection, highly efficient methods for separation of substances like micro electrophoresis and micro chromatography, which may reduce analysis times by orders of magnitude due to miniaturization, material transport systems, which will work with amounts of substances in the picolitre range, and numerous methods for surface fictionalization with biomolecules characterize the present-day state of technology [17]. In this context, micro technology is becoming one of the most important tools for drug development in life sciences, but will also have a decisive and fundamental effect on comprehensive medical diagnostics. Labs on a chip will usher in a revolutionary development.

In this context, medical diagnosis with highly parallel analysis units on a chip-like device may be regarded more and more as a part of information technology. Therefore, it is not surprising and quite logical that leading IT companies, in particular in the USA, regard chip-based medical diagnosis as an extremely promising business opportunity and spend huge financial means to explore this field. These companies are clearly aware of their inherent strength in this field, which comprehensively covers micro fabrication capabilities, handling of large amounts of data and extremely fast pace of development.

At present, it is still open whether the IT companies will be able to take over the diagnostic business from the traditional pharmaceutical companies. However, it is absolutely clear that the upcoming competition between IT and pharmaceutical industries will accelerate the progress in this field where the winners will make extremely large profits in the future by utilisation of micro technology.

7. Information and communication

The progress in most hardware for information and communication technology will be mainly determined by the continuous advance of microelectronics in still many years to come. Nevertheless, the market share of micro technology in IT will steadily increase and more and more products will be equipped with components and systems of micro technology. This evolutionary development started many years ago and a number of examples like read-write-heads for hard disk memories, laser heads for CDs and DVDs, ink jet printer heads or surface acoustic wave (SAW) filters for mobile phones characterize this process. Meanwhile, micro devices add up to a market volume of more than ten billion US $ per year not including products like CDs or DVDs which are micro components by themselves carrying information in micron sized pits on their surface.

It is hardly possible to give a comprehensive overview of the role of micro technology in this context. Therefore mainly optical micro devices will be considered which are beginning to be implemented on a wide front in information and communication technology. Fibre optical networks will reach data rates close to peta bits per second \((10^{15} \text{ b/s})\) within few years and become also standard for home application, but fibres make up only a small part of the total technological and commercial expenditure. A wide variety of photonic micro devices are required in huge numbers for their realisation. These are active elements like diode lasers, receiver diodes, fibre optical laser amplifiers and complex optical switching systems. Equally, passive optical micro components are needed like couplers, splitters, connectors, micro lenses, narrow-band filters, and complex systems for dense wavelength division multiplexing (DWDM). In addition, systems like optical back planes for high-speed data exchange or opto-electrical hybrid systems according to the fibre-on-board concept utilise micro optical and micro mechanical alignment components. Previously the high price for such network components still held back the wider use of optical communication technology, but micro technology
will solve this problem. Micro fabrication by means of LIGA technology for instance allows to reduce production costs even on a laboratory scale by more than an order of magnitude with respect to conventionally produced optical elements [18].

In the same way as for semiconductor materials in which certain energy ranges are not accessible, periodic structures with dimensions in the micrometer or submicrometer range show wavelength ranges which are not allowed for the photons, i.e. a photonic band gap exists. Such periodic three-dimensional microstructures or “artificial crystals” can be produced using micro fabrication methods. There are a wide variety of application opportunities for photonic band gap materials in communication technology, in laser technology and optical analysis. Wave-guides, in which light can be deflected by large angles practically without losses, will presumably permit a compact construction of optical systems similar to that of microelectronic circuits. Mirrors, resonators, modulators, dispersive structures and other functional elements expand the spectrum of applications. It is to be expected that the first components based on this technology will be offered commercially in a few years and the product spectrum of micro technology will increase further.

Micro fabrication methods are also applied in just all kinds of flat panel displays. Liquid crystal displays (LCD) use voltage controlled arrays of micro valves for polarized light for image generation. Micro plasmas ignited in small channels for exciting phosphors are applied in brilliant large area flat panel plasma displays (PDP). Field emission displays (FED) generate light in phosphors by means of energetic electrons extracted from sharp micro tips. Excellent results were recently obtained with so-called electronic paper where micro spheres filled with a dark liquid and white particles are embedded in a thin foil and white or dark pixels are obtained by electrophoretic migration of the particles in an electric field. Another variant of electronic paper uses rotatable micro spheres with black and white halves. The status of the pixels is determined by the electrically addressable orientation of the spheres. The most exciting development in view of low costs, large area images, brightness, low power consumption, and mechanical flexibility are displays using organic light emitting materials (OLED). Light is generated at various wavelengths in thin organic films by recombination of electrons and holes as in well-known inorganic LEDs.

Real micro systems are digital multi mirror devices (DMD) for image projection, which have to be regarded as a highly promising alternative to large area flat panel displays. Silicon chips with more than a million movable mirrors actuated by means of electrostatic forces are used to generate high-resolution images. Besides LCD micro displays, DMD chips are the key elements for portable digital projectors. At present, DMD projection systems are also finding their way into cinemas. They are still three times more expensive than standard projectors, however, they offer the chance to replace the heavy film copies by a few digital videodiscs with just no quality loss by multiple use or ageing.

8. Mobility

Mobility is a term with many facets and also many links with micro technology. Micro devices in modern automobiles, airplanes and other transportation systems for persons and goods support mobility by improved control, reliability, safety, and comfort and offer a wide variety of possibilities to reduce fuel consumption and environmental pollution. Micro technology leads to higher mobility by reduction of weight and space of portable consumer products and other technical devices we have to carry with us and it is an essential basis for continuous improvement of their performance. Recent development work deals with so-called palm power systems with the aim to increase the capacity of energy storage devices by an order of magnitude compared to advanced batteries. This work is mainly focussed on miniaturized fuel cells with an integrated micro reformer to generate gaseous hydrogen from a liquid hydrogen compound. Microsystems like cardiac pace makers or hearing aids and most other organ supporting micro devices are also of essential importance for our mobility.

A modern mid-class car has some ten to twenty micro sensors for motor management to measure various pressures, mass flow rates, engine knock, and combustion gas composition [19]. In addition, air bag systems are equipped with micro acceleration sensors and micro ignition systems, the key elements of the electronic stability program are gear rate micro sensors and micro sensors also monitor the air composition in cars. Further improvements in safety and road holding will be achieved by means of optical microsystems for detection of black ice and surface acoustic wave sensors will be directly built into tires to deliver data about deformation, temperature and other properties important for safety and roadability. Micro infrared camera systems for night vision and rear-view mirror systems without blind angle are also under investigation. In order to save costs, space and weight and to improve performance and reliability,
Multipurpose integrated micro sensor systems are presently developed for simultaneous and redundant control of modern automobiles.

In addition to micro sensors, other micro devices are becoming more and more important for automotive technology. Micro fabrication methods like micro electro discharge machining are applied to manufacture nozzles with multiple holes for direct injection Diesel motors. Optical micro devices are needed for replacement of the electric cable harness by a polymer optical fibre system to handle the steadily increasing data rates. Relatively soon the automobile will become a mobile multimedia platform. As a first step in this direction the standard dashboard will vanish and cars will be equipped with a freely programmable dashboard using flat panel technology to deliver the information required according to the driving conditions. Further flat panel displays will be installed for navigation, night vision and entertainment.

The importance of micro technology for aircraft and space flight is similar to that for automobiles. The data rates for aircraft control are steadily increasing and it is to be expected that the fly-by-wire concept will be replaced by the concept of fly-by-light requiring again micro optical network components. The increasing demand for comfort and entertainment of the passengers aims also at an extension of the optical network and the demand for bright high-resolution flat panel displays will increase continuously. A multitude of micro sensors and sensor arrays or matrices will be needed to realize adaptive wings whose shape is adjusted according to flight conditions or to monitor continuously the mechanical status of the complete airframe. However, this is not a program for the near future. Less challenging is the concept to reduce drag and, correspondingly, fuel consumption by coating the airplane with a foil with micro riblets having a structure similar to sharkskin. According to first tests a five percent reduction of fuel consumption seems possible.

9. Micro reactors for sustainable development

Since some ten years, researchers in chemical engineering are intensively analyzing the possibilities offered by miniaturization and integration to achieve a radical change in design philosophy for chemical plants, which they call process intensification [20]. The main intention is to realize lower investment, operating, and maintenance costs for chemical plants without decreasing their production capacity by means of a dramatic decrease in plant size. Consequently, this concept aims at an extreme reduction of the dimensions of process devices as well as integration of reaction and unit operation elements to save space and energy. Micro reaction technology will lead to a new era of chemistry, biotechnology and chemical engineering [21,22].

Smaller characteristic dimensions are favorable for various fundamental reasons. The driving forces for heat and mass transfer increase with the gradients of temperature and concentration so that, for a given difference in these properties, correspondingly higher mass and heat fluxes are achieved at smaller dimensions. Furthermore, the ratio of surface area to volume is the higher the smaller the dimensions are so that exchange processes are correspondingly enhanced. Because of the small volume and hold-up, respectively, and the large specific transport rates, extremely short response times exist which simplify process control considerably. The combination of these facts results in a nearly inherent safety of the plant. Since the flow and transport conditions can be adjusted precisely the residence time of a chemical reaction can be exactly determined to achieve optimum yield and selectivity. As a matter of principle, there is no strict limit in size reduction of plant components since any production capacity is achievable by means of parallel operation of process items. This mode of operation corresponds to the fundamental concept of nature, which uses its micro reactors, i.e., the living cells, also in parallel to produce the required quantities of substances. The concept of scale up is thus replaced by the concept of numbering up, which is superior, by a much higher flexibility.

According to the extremely wide variety of reactions, educts, products, and process conditions, a sufficiently broad spectrum of materials and micro fabrication technologies is required to realize suitable micro devices for chemical processes. Since material is transported in every plant, three-dimensional manufacturing processes have to be applied to realize sufficiently large cross-sections for material transporting channels and ducts as well as reaction volumes. Using the methods described in Sections 3 and 4, a multitude of micro reaction devices were manufactured for research purposes, which can be operated in an extremely broad range of precisely controllable process conditions.
Micro reactors are powerful tools for process development and have been successfully applied for improvement of established chemical processes in industry and for finding novel commercially interesting reaction routes. Micro components for the unit operations of a chemical technology as well as integrated micro reaction systems have been produced comprising mixers, reaction vessels, valves, pumps, extractors, heat exchangers and a wide variety of fluidic devices with channel structures in the micrometer range. Meanwhile, micro reaction devices are even applied in a few cases for the commercial synthesis of fine chemicals. Moreover, novel concepts are under investigation aiming at mass production of commodities.

Corresponding to labs on a chip, arrays of micro reactors are used in combinatorial material science to find novel functional materials like catalysts, fluorescent compounds or organic semiconductors by high throughput synthesis and screening of a huge amount of substances in a short period of time, typically some hundred or even some thousand per day. This task could never be solved economically by means of macroscopic devices when just considering the amount of waste generated in the high throughput process. In addition, technical and financial problems would strongly limit the necessary degree of parallelisation when macroscopic technology would be applied.

After a relatively short period of fundamental research, chemical and pharmaceutical industry has begun to exploit the innovative technological and commercial potential of micro reaction technology. Due to the higher yields and selectivities, the application of environmentally more favorable reaction routes, and the possibility to replace large plants by small plants for distributed production according to the actual demand, it is to be expected that micro reaction technology will contribute essentially to sustainable development. The results of research can be implemented more quickly and, of course, it is far simpler to react flexibly to changes in the market.

The technological advancement in micro reaction technology has become fast and a chance is given to industry for progress and profit in this new field of micro technology. Attractive business opportunities exist in cost effective production of chemicals, fabrication of micro reaction components, systems, and facilities as well as in offering corresponding services in advanced chemical engineering including design and mathematical modelling of novel reaction concepts.

10. Outlook

Micro technology has already been running very well for several years now and a fast growing multi-billion dollar market has been established. But micro systems are like brownies, which do their work secretly, and you only notice them when they no longer work. Since micro systems are reliable and function almost invariably, we do not notice this and thus do not realize their existence. This is more or less irrelevant for the normal customer who buys a macroscopic product equipped with micro devices, which he may never see during the product life. However, an industrial company whose existence depends on technological innovation may run into serious difficulties if it ignores micro technology.

In the future, the progress of micro technology will be even faster and will create ever more micro products for novel applications. As a matter of fact, the somehow confusing multitude of products and applications makes a simple access for beginners sometimes quite difficult and there is still a huge problem of awareness concerning the commercial potential of this multi-billion $-market for many industrial companies. However, it is worth to take the chance and to analyze comprehensively the commercial potential. Return on investment is achievable not only with micro technological products but also for industries aiming at the production of process equipment and special materials for micro technology. A particularly high demand will exist for services in the field of design and mathematical modeling concerning micro fabrication processes as well as functional behavior of micro components and systems.

The high speed of development of micro technology will result in a dramatic change and challenge for research. High investments for equipment are necessary to keep up with the fast pace of development and experts in micro technology expect salaries adequate to the high requirements they must meet in generating commercially attractive innovations. A lot of money will be made in the course of this race. The development will be similar to that of biotechnology where, in particular in the USA, research activities passed over more and more rapidly from public research institutes to private research companies. They have better prerequisites to get adequate financial means in order to meet the requirements of
a highly competitive environment and to generate corresponding organisational structures. In every respect, micro
technology has become a highly competitive global business with great chances for progress and profit.

References