Micro and nanoprocessing techniques and applications

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Nanotechnology is a rapidly growing field with many and important applications. Technologies associated with this field aim towards the manufacture of improved quality products that are suitable for devices that are lighter, faster, more reliable, efficient and safer and in those respects more economical for sophisticated industrial products that perform better and are more advantageous in many other ways than any other devices manufactured so far. The realization of this production is achieved through processing techniques as sophisticated the devices themselves, either specially designed for this technological field or suitably altered processing for manufacturing large-scale super-finished products or miniaturized devices. Some of these micro and nanoprocesses, under the general term *ultraprecision processes*, are outlined in this paper. Furthermore, some important application fields in current and future technologies are reported in order to specifically indicate the great impact of these processes in today's industry, which also shall lead to the emerging technologies of tomorrow.

1. Introduction

The demands of today's industry lead towards the continuous refinement of manufacturing processes as far as the achieved precision is concerned. Large-scale components such as precision moulds, machine elements, mirrors and lenses require micrometer or sometimes nanometer tolerances and surface finishes. At the same time microparts are introduced in several applications, whose functioning would otherwise be impossible. The most characteristic example is the integrated circuit (IC) industry, which creates parts that have micrometre dimensions or possess features with nanometre size. Furthermore, microelectromechanical systems (MEMS), which usually contain microsized mechanical parts, are becoming more and

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more popular in engineering. The outcome is the generation of applications that are efficient, reliable, environmentally friendly and more economical.

The above mentioned trends are based on disciplines that are interdependent and need to be taken into account. The technologies required are either new ones developed purely for their application in this specific field or ones that are currently in use and are being further extended in order to accomplish the task. The realization of state-of-the-art miniature devices is achieved through highly advanced manufacturing processes, which are able to provide the required tolerance, roughness and size. This is achieved by developing new machine tools and control systems and even wholly novel processes. This should be combined with techniques that can observe and measure features at nanometre and subnanometre levels and even manipulate atoms with subnanometre control, and new modelling and simulation techniques that are used for the prediction of the salient properties of the products and help to acquire an insight into the mechanisms involved in processing at this level—to understand the fundamentals of processing at micrometre, nanometre or molecular scales.

Processes can be classified according to their precision. This is especially important in the case of the material removal processes where the search for ever greater accuracy is continuous. According to Taniguchi three categories can be distinguished: normal, precision and ultraprecision processes.[1] The borders between each pair of categories are defined as a function of process precision relative to that of other processes: for example, what was considered to be ultraprecise in the 1980s is today only precise, due to advances in technology. There is therefore no uniform definition of ultraprecision processes, other than that they are the most extremely accurate processes of their epoch.

Recently the term *micromachining* was introduced. It is frequently used for describing ultraprecision processes aiming towards the production of microparts and miniaturized components. Miniaturization machining operations have evolved to one of the key technologies in the field of micro and nanoprocesses, yet a commonly accepted definition of micromachining is lacking. Masuzawa states that "micro" literally represents the range between 1–999 μm.[2] However, since small components introduce difficulties during their manufacturing compared to macro components, "micro" should incorporate the meaning that something is too small to be machined easily. Furthermore, taking into account the epoch, machining method, type of product or material the range 1–500 μm was finally adopted to delineate the upper and lower limits of micromachining. However, it is very common to shift this range to 0.1–100 μm and include, as well as the size of a component, its accuracy or surface texture.[3,4] Moving downwards

[1] N. Taniguchi, "Current status in, future trends of, ultraprecision machining and ultrafine materials processing". *Annals of the CIRP* **32/2** (1983) 573–582.

[2] T. Masuzawa, "State of the art of micromachining". *Annals of the CIRP* **49/2** (2000) 473–488.

[3] M.J. Madou, *Fundamentals of Microfabrication: the Science of Miniaturization*, 2nd edn. Boca Raton: CRC Press (2002).

[4] L. Alting, F. Kimura, H.N. Hansen and G. Bissacco, "Micro engineering". *Annals of the CIRP* **52/2** (2003) 635–657.

from 0.1 μm (= 100 nm)[5] the region defining *nanotechnology* is entered. A broadly accepted definition is that nanotechnology pertains to the processing of materials in which structure of a dimension of less than 100 nm is essential to obtain the required functional performance.[6] Similarly to micromachining, nanotechnology's régime extends from 0.1 to 100 nm and includes the ability to observe and measure features at this scale. Theoretically, the limit of nanotechnology is the processing of atoms, the diameter of an atom being about 1 Å.[7] Figure 1 illustrates some components produced by micro- and nanoprocesses in order to apprehend the size of such components.

The aim of this paper is to describe some micro and nanoprocessing techniques, present their applications in contemporary industry and make speculations for the future. It is not possible to discuss all the techniques available today within this paper but some of the most applied and the most promising for the future are selected; their main characteristics, capabilities and applications are outlined. Most of the techniques presented are material removal processes. Material removal is achieved by various methods according to the principle the process is based on. In the following paragraphs the processes presented are categorized according to these principles. Their advantages and disadvantages and the precision they can attain are discussed and their capabilities are compared.

2. Types of micro and nanoprocesses

Micromachining and nanotechnology can be achieved by means of various methods and techniques. However, in all the cases examined the trend towards smaller dimensions, higher accuracy and production of components that are highly functional is common. The development of new technologies follows mainly two directions: the downscaling of manufacturing processes that have an existing background as conventional ones and are already widely used in industry, and the development of new ones that are suitable only for this kind of manufacturing.

It is usual, and this classification will be followed hereafter, to distinguish between lithography and non-lithography based micro and nanoprocesses. This is due to the wide spread of lithographic processes, especially photolithography, for the manufacture of ICs. Although photolithography has served for many years as the exclusive process used for silicon chips it seems that it has reached its limits and that is why new lithographic processes are being introduced. Some of these processes, often called Next Generation Lithographies (NGL), are presented in what follows and their advantages and disadvantages are discussed. X-ray lithography, Lithographie, Galvanoformung und Abformung (LIGA), electron beam lithography and 3D lithographies among others will be discussed.

The non-lithography based processes include mainly machining operations that use mechanical, thermal, electrothermal or electrochemical energy in order to achieve material removal. In this

[5] 1 micrometre (μm) is one millionth of a metre. The nanometre (nm) is one thousandth of a micrometre.
[6] J. Corbett, P.A. McKeown, G.N. Peggs and R. Whatmore, "Nanotechnology: international developments and emerging products". *Annals of the CIRP* **49/2** (2000) 523–545.
[7] An Ångstrom unit (Å) is 0.1 nanometres (nm).

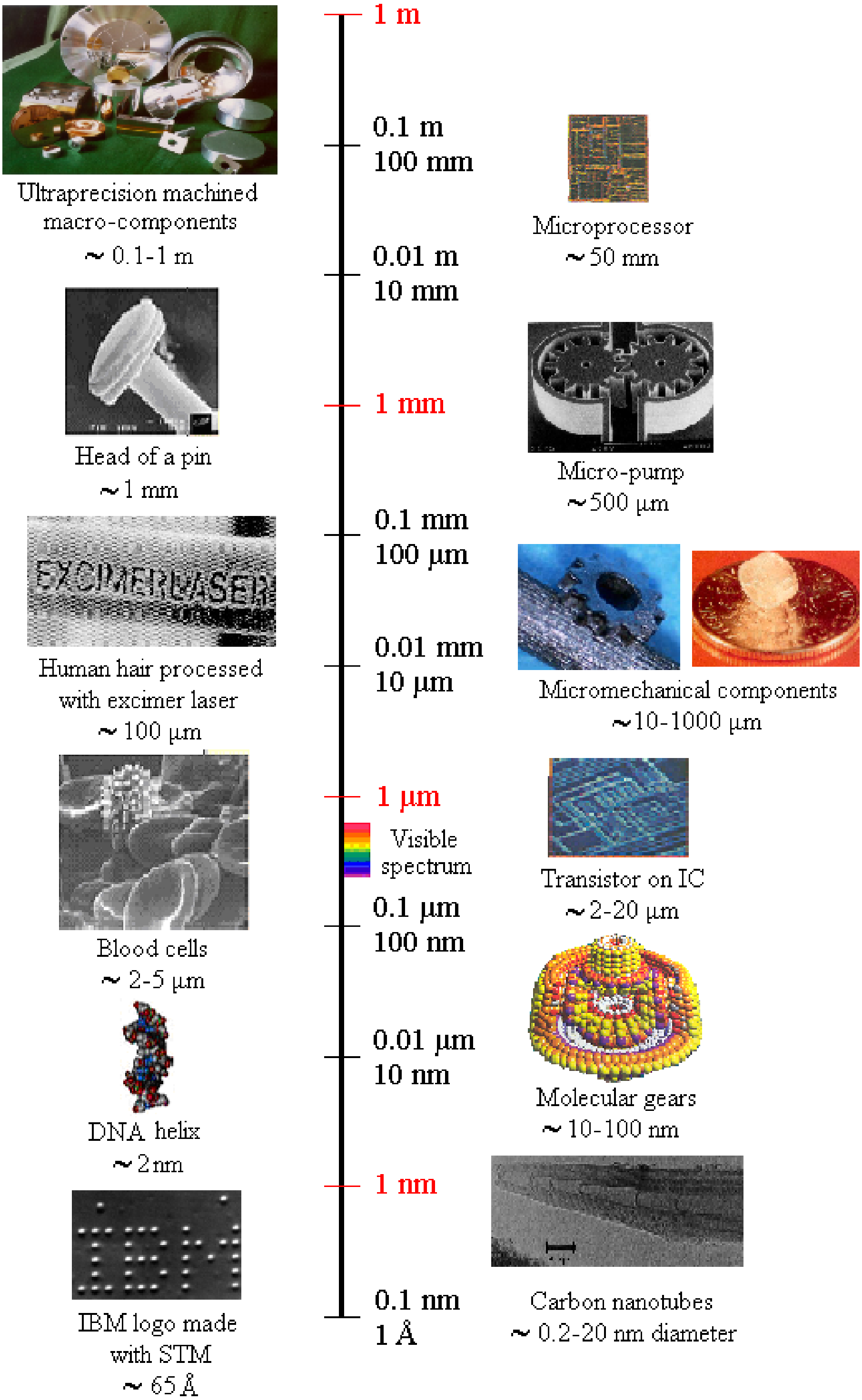

Figure 1. Size scale and examples of micro- and nanocomponents.

category conventional and non-conventional machining processes are included, suitably altered to perform in the microworld. Some of the processes examined are microcutting, micro-Electrical Discharge Machining (micro-EDM), laser processes and electrochemical machining.

Our aim is not to describe all micro and nanoprocesses thoroughly and in detail; for that an adequate number of references to the relevant literature is provided. The aim is rather to describe some of them, depict some of their important characteristics and emphasize the differences that make these processes unique and promising. In the case of lithography-based processes, photolithography is the main subject. NGL are also analysed and their advantages or disadvantages in comparison to photolithography are pointed out. In the case of non-lithography-based processes, a variety of them are described and compared. Furthermore, owing to the fact that they are also realized as macro as well as microprocesses, the differences between the two types are elaborated. This analysis points out the difficulties arising from transferring technology between the macro- and microworlds and leads to the fact that sometimes a feature that is considered as an advantage in one world may be a disadvantage in the other and vice versa. Some important applications are described so that the reader can have an idea about how these technologies are applied in everyday life.

3. Lithography-based processes

Lithography is a combination of two Greek words, namely *lithos* (stone) and *graphein* (write), and refers to a kind of art invented in the late 1700s involving the transfer of an original image or pattern carved on a stone onto paper. This kind of art has been the inspiration for a technology, the most widely used form of which is photolithography (from another Greek word meaning light), used in the IC industry for the production of chips.

3.1 Photolithography

In Figure 2 the basic steps followed during photolithography can be seen. In this example an oxidized Si wafer is used and a simple pattern must be transferred onto it. In Figure 2 (a) the oxidized wafer is coated with a photoresist layer (resist), a polymer sensitive to ultraviolet (uv) light approximately 1 μm thick. Then a mask is placed on the resist, Figure 2 (b). The mask (also referred to as a photomask) is the stencil used to repeatedly generate a desired pattern on the resist coating to be finally transferred to the oxide. It is an optically flat glass, some parts of which are covered with a metal layer, usually chromium, forming the pattern. The glass parts of the mask are transparent to uv while the chromium plated ones absorb it. The resist is exposed to uv, which passes through the mask, and depending on its type, so-called negative or positive, the resist is altered. In negative resists uv hardens the areas exposed to it, while in positives the opposite happens. In Figure 2 (c) an example of a negative resist is given, where the negative image of the mask is transferred onto it.

After exposure, the wafer is rinsed in a developing solution or sprayed with developer, which removes the unexposed areas of the resist and leaves a pattern of bare and resist-coated

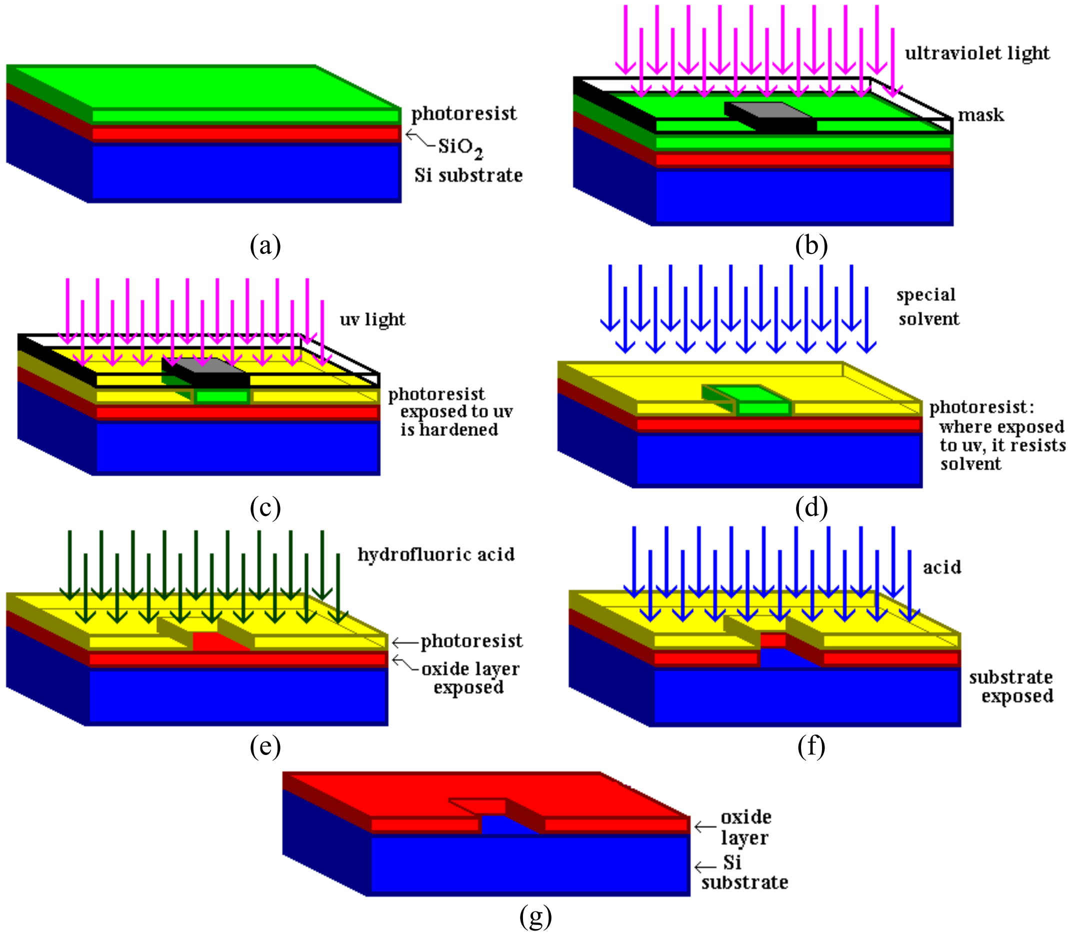

Figure 2. The basic steps of photolithography: (a) photoresist, oxide and silicon substrate, (b) application of mask and exposure to ultraviolet light, (c) exposed photoresist is altered, (d) part of the resist is removed by a special solvent, (e) etching of the oxide, (f) removal of photoresist (g) creation of feature (after D.A. Fraser, *The Physics of Semiconductor Devices*. Oxford: Clarendon Press (1983)).

oxide on the wafer surface, Figure 2 (d). In the next step after development, the wafer is placed in a solution of hydrofluoric acid (HF) or acid buffered with ammonium fluoride (HF + NH_4F), meant to attack the oxide but not the resist nor the underlying silicon; the resist protects the oxide areas it covers, Figure 2 (e). Once the exposed oxide has been etched away, the remaining resist can be stripped off with a strong acid, such as sulfuric acid (H_2SO_4), attacking the resist but neither the oxide nor the silicon, Figure 2 (f). The oxidized Si wafer with the etched cavity in the oxide, Figure 2 (g), serves as a final product that has been appropriately formed or can be further processed. For example, the cavity can be filled by depositing a desired material, or a new resist layer can be added and a new feature with a new mask can be created, repeating the steps described in Figure 2 (a)–(f).

Negative and positive resists have characteristics that make them suitable for certain applications in the IC industry. These characteristics have to do with their ability to adhere to Si, the minimum feature size that can be produced, their available compositions and the developers used, thermal stability and other properties, and cost.[3,9] Moreover, there are also permanent resists that are not removed during the process, in contrast to the resist in the example. As far as the position of the mask relative to the resist is concerned, there are a few possibilities: the mask can be in actual contact with or merely in proximity to the resist. In the first case, the hard masks, as they are called, wear easily and cannot be used many times. In the second case, soft masks are placed approximately 10–20 μm above the resist. In both cases, described as shadow printing, the pattern is transferred as a 1:1 image. A more reliable method is projection printing, where the mask is focused by a high resolution lens system onto the resist. That way the mask is not subjected to wear while reduction of the pattern by a factor 1:5 or 1:10 is possible. Additionally step-and-scan systems are used, where the mask or the wafer are moving and after the image of one chip is printed at a certain location of the wafer, the system steps to the next location where the next chip is printed, and so on. In this way hundreds of ICs are printed on one wafer and productivity is enormously increased.

Small sizes and continuous further shrinkage in the IC industry are indeed essential for its future. Chip structures have become very compact and the large number of transistors packed closely together has allowed computer speeds to increase, since the electrical signals have less distance to travel between two transistors. Small microchip sizes have resulted in smaller, less power-consuming and yet more powerful computer systems. In order to keep up with Moore's "law" further shrinkage of individual transistor dimensions must be achieved, which requires further refinement of the manufacturing. New techniques are being introduced that aim at the improvement of photolithography's resolution. These techniques, collectively called RET (resolution enhancement technologies), focus on the improvement of resists and masks. Resist improvement includes chemically amplified resists, such as SU-8, and resists that are sensitive to shorter wavelengths, while mask improvement focuses on techniques that can reduce the bothersome diffraction of light, using phase-shifting masks (PSM) and grey-tone masks (GTM) that notably increase the efficiency of optical elements. Nevertheless, the smallest feature that can be manufactured, even with these improvements, is about half the wavelength of the radiation used. The usual excimer lasers used today as uv sources have wavelengths of a few hundred nm resulting in features with dimensions around 100 nm. The search for shorter wavelengths and improvements in photolithography for the manufacturing of microstructures has led to the development of new lithographic techniques known as NGL technology, which are discussed in the following paragraphs.

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[9] N. Taniguchi, *Nanotechnology: Integrated Processing Systems for Ultra-Precision and Ultra-Fine Products*. Oxford: University Press (1996).

3.2 Next Generation Lithographies (NGL)

Continuous improvement of traditional photolithography has delayed the development of wholly new methods for the fabrication of ICs. Equipment cost and technical reasons have been obstacles in the research and development of NGL, and their industrial adoption. The methods discussed below are probable candidates for the production of chips in the future.

A plausible extension of uv photolithography is Extreme UV Lithography (EUVL), which uses laser-produced plasmas, or synchrotrons, to generate wavelengths of 10–14 nm. The very short wavelength is an advantage but unfortunately EUV is absorbed by almost every material and the process must take place in a vacuum. Furthermore, all the usual optical accessories are reflective and not refractive at this wavelength and new resists must be developed that are sensitive to this wavelength. There are also some technical problems related to EUV sources and a lot of research is currently focused on that topic.[10–12]

Another promising technique is X-ray lithography, where instead of uv light X-rays are used. The X-ray wavelength is about 10 Å and diffraction effects are negligible. This method uses no optical equipment, which seems to be an advantage, but is also a disadvantage because only 1:1 shadow printing can be performed. Thus the mask must have the same dimensions and dimensional tolerance as the product, making its manufacturing a real challenge for micro- and nanoprocesses.[13] The most important technical problem is however the X-ray source that should be used. One possibility would be to use the radiation emitted by electrons as they circulate in a synchrotron storage ring, but the cost for such an installation is prohibitive. Some industries have developed their own X-ray lithography systems and use it mainly for the production of electronics. Indeed, a method for producing 3D structures using X-ray lithography has been reported. Conventionally, during the X-ray exposure, the mask and the substrate are mounted perpendicular to the beam, resulting in vertical profiles. When the mask and the substrate are tilted with respect to the beam, inclined profiles may be produced. In Figure 3 a gold microfluidic channel is presented. In the same figure, in the inset, the construction of this component by two X-ray lithographic tilt exposures is illustrated.

LIGA is a process based on X-ray lithography and involves some additional steps. In its original form, in the first step of the process X-rays are used to expose a thick layer of resist to a depth up to 1000 μm, with a lateral resolution of better than 1 μm. After exposure a resist mould

[10] V.Y. Banine, J.P.H. Benschop and H.G.C. Werij, "Comparison of extreme ultraviolet sources for lithography applications". *Microelectronic Engineering* **52** (2000) 681–684.

[11] R. Lebert, L. Aschke, K. Bergmann, S. Düsterer, K. Gäbel, D. Hoffmann, P. Loosen, W. Neff, P. Nickles, O. Rosier, R. Poprawe, D. Rudolph, W. Sandner, R. Sauerbrey, G. Schmahl, H. Schwoerer, H. Stiehl, I. Will and C. Ziener, " Preliminary results from key experiments on sources for EUV lithography". *Microelectronic Engineering* **57–58** (2001) 87–92.

[12] S.R. Mohanty, C. Cachoncinlle, C. Fleurier, E. Robert, J.-M. Pouvesle, R. Viladrosa and R. Dussart, " Recent progress in EUV source development at GREMI". *Microelectronic Engineering* **61–62** (2002) 179–185.

[13] For an overview on the making of X-ray lithography masks and resists see footnote 3 and S. Ohki and S. Ishihara, "An overview of X-ray lithography". *Microelectronic Engineering* **30** (1996) 171–178.

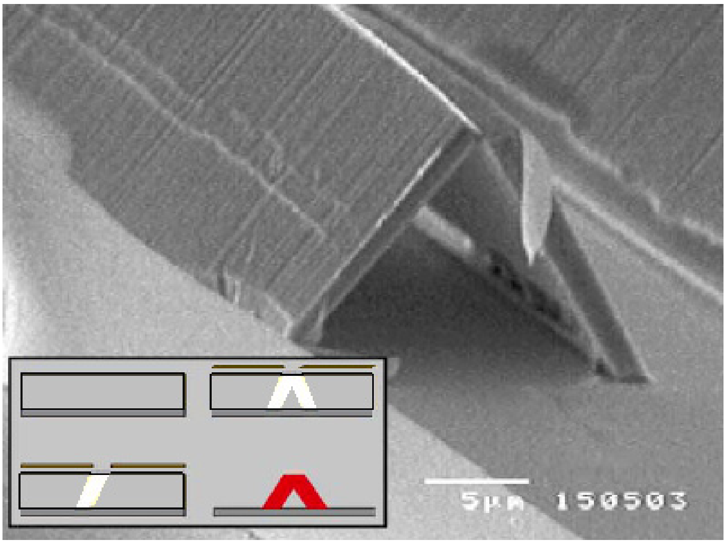


Figure 3. Scanning electron micrograph of a microfluidic channel produced by X-ray lithography. Inset: processing sequence (from F. Romanato, M. Tormen, L. Businaro, L. Vaccari, T. Stomeo, A. Passaseo and E. Di Fabrizio, "X-ray lithography for 3D microfluidic applications". *Microelectronic Engineering* **73–74** (2004) 870–875).

is produced that is the replica of the mask pattern. Then, depending on the material and number of parts required for the final product, different fabrication routes can be chosen: the polymer can be used as it is, as in X-ray lithography, or it can be subjected to electroforming and moulding techniques. In the application of electroforming techniques the polymeric mould is filled with metal or ceramic. The resist is removed and metallic or ceramic microparts are produced. Alternatively, by the same method a metallic mould is produced that can be used several times to mould replicates from other materials, primarily plastics. Several types of moulding processes have been used and the resulting plastic part may again serve as a mould, like the original resist structure, for fast and cheap mass production since there is no need for a new X-ray exposure. LIGA is characterized by tight tolerances and high precision, and 3D structures can also be constructed by tilting angles, as described above. Sometimes, deep X-ray lithography is used as a first step, or other sources of radiation such as conventional photolithography or uv light from low-cost excimer lasers. The applications of the method are many and interesting and involve the manufacturing of MEMS, micromotors, sensors, nozzles, moulds for micro-fibres, optics and high precision tools.[16–18]

[16] C.K. Malek and V. Saile, "Applications of LIGA technology to precision manufacturing of high-aspect-ratio micro-components and -systems: a review". *Microelectronics Journal* **35** (2004) 131–143.
[17] Y. Hirata, "LIGA process-micromachining technique using synchrotron radiation lithography-and some industrial applications". *Nuclear Instruments and Methods in Physics Research* **B 208** (2003) 21–26.
[18] Y. Cheng, B.-Y. Shew, M.K. Chyu and P.H. Chen, "Ultra-deep LIGA process and its applications". *Nuclear Instruments and Methods in Physics Research* **A 467–468** (2001) 1192–1197.

A process that allows the fabrication of lines much less than 100 nm thick is Electron Beam Lithography (EBL), which uses high-energy electrons to expose electron-sensitive resists. This method, like X-ray lithography, does not practically limit the obtainable feature resolution due to diffraction and furthermore there is no need for a physical mask, but a software mask is used instead. The pattern is stored in a computer and the beam is directed to the appropriate area enabling the pattern to be written sequentially, point by point, over the whole wafer. This makes the process rather slow, even though arrays of electron beams can be used. Other disadvantages of the method are that electrons readily scatter in solids, limiting resolution to dimensions greater than 10 nm, and that the process has to be performed in a vacuum. All these, and the high cost of the equipment, have limited the application of EBL to specialized applications, including mask-making for other lithographic techniques.

A technique known as SCALPEL (SCattering with Angular Limitation Projection Electron beam Lithography) has been developed by Lucent Technologies. It is a projection electron beam technique employing a step-and-scan system (Figure 4). A membrane made from a low atomic number compound, such as silicon nitride, is used as a mask, with an overlaid high atomic number material (typically tungsten) used to make the pattern. High-energy (100 keV) electrons uniformly illuminate the mask and electrons passing through the pattern are scattered while those passing through the membrane suffer very little scattering. A projection system with two lenses performs a 4:1 reduction of the pattern. An aperture in the back focal plane of the second lens stops the strongly scattered portions of the beam, producing a high contrast image at the wafer plane. The small images at the wafer plane are stitched together by suitably moving the mask and the wafer, which are servo-controlled using a laser interferometer system. A system named SCALPEL-Proof of Concept was created in 1996 for testing the method and features of 80 nm were produced.[19]

A related kind of processing is Ion Beam Lithography (IBL), which is a category of lithography-based processes with great future potential. One kind of IBL is Focused Ion Beam (FIB) machining, where electrons are replaced by high energy ions of a volatile metal (typically gallium). Beam diameters of less than 50 nm are achieved and as in the case of EBL no mask is required. Other variants are Deep Ion Beam Lithography (DIBL), which employs high energy protons, and Ion Projection Lithography (IPL) where protons are generated by a radio frequency-driven filament.[3,9,20] IBL has certain advantages over EBL; it has better resolution because ion scattering is negligible in the resist and the resist sensitivity is much higher. IBL spot size is the smallest possible among uv, X-ray and electron beam spots, the FIB spot size being about 8 nm.

[19] L.R. Harriott, S.D. Berger, C. Biddick, M.I. Blakey, S.W. Bowler, K. Brady, R.M. Camarda, W.F.Counelly, A. Crorken, J. Custy, R. DeMarco, R.C. Farrow, J.A. Felker, L. Fetter, R. Freeman, L.Hopkins, H.A. Huggins, C.S. Kuurek, J.S. Kraus, J.A. Liddle, M. Mkrtychan, A.E. Novembre, M.L. Peabody, R.G. Tarascon, H.H. Wade, W.K. Waskiewicz, G.P. Watson, K.S. Werder and D. Windt, "The SCALPEL Proof of Concept system". *Microelectronic Engineering* **35** (1997) 477–480.

[20] R.A. Lawes, "Future trends in hgh-resolution lithography". *Applied Surface Science* **154–155** (2000) 519–526.

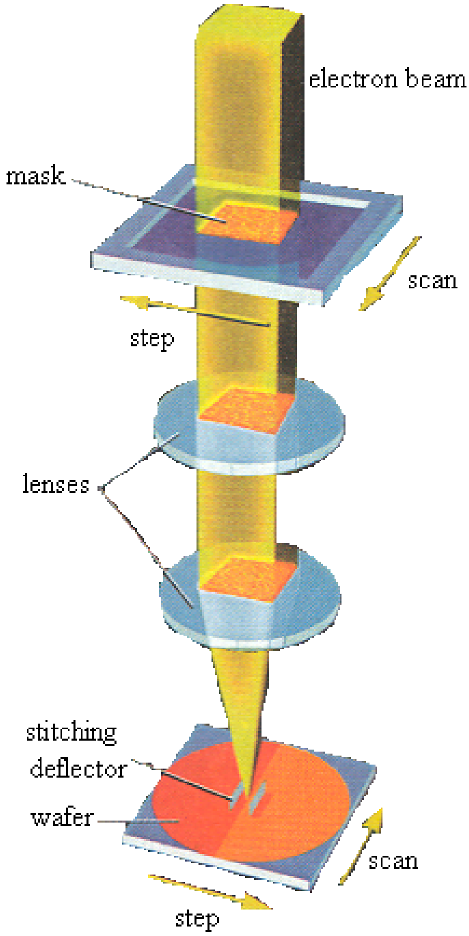


Figure 4. Schematic of the SCALPEL method system.

Traditional lithography techniques result in projected 2D structures rather than 3D shapes. With the exception of some NGL techniques mentioned above, lithography cannot produce curved surfaces, which are sometimes needed in micro- and nanoapplications. For facing this problem 3D lithography methods have been developed, such as holographic lithography (HL) and stereolithography (SL). In HL the mask is replaced by a holographically constructed one and a hologram of the pattern is made on the resist layer. In SL, in a procedure similar to rapid prototyping, light exposure solidifies liquid resin into the desired 3D shape. Research is under way to improve these processes and their applications, especially in the fields of micropart construction, biomedical engineering, actuators and tools.[3]

4. Non-lithography based processes

The processes included in this section are conventional and non-conventional machining processes, which are being used in traditional manufacturing as well as in the nanorealm. They are at the forefront of industrial integration and their applications have reached a high level of production maturity. Some of them have the prefix “micro” in their names to declare that they are processes following the same principles as the original macroscopic ones, but particularly designed as microprocesses. A wide variety of processes could be included here, but to avoid undue length some characteristic ones only will be described. It should be noted that unlike lithography-based processes they are not used in the IC industry, but this certainly does not mean that they are not suitable for micro and nanoprocessing. On the contrary, they have advantages related to the fact that they can produce 3D structures for a variety of materials, including metals and hard and brittle substances with fine tolerances and high accuracy. The processes described will be subdivided into categories according to the kind of energy they use for machining, namely mechanical, electrothermal, thermal and electrochemical.

4.1 Mechanical processes

Mechanical processes are probably the most popular among the microprocesses in current use. They involve mechanical interaction between a sharp tool and the workpiece causing the removal of unwanted material in the form of a chip. Conventional machining operations such as turning, milling, grinding and drilling belong to this subdivision. Advances in the subsystems involved in macroscopic machining such as positioning, automation, numerical control, metrology and tools have made it possible to apply them in microfabrication.[21,22] In particular, the “micro” versions of the aforementioned processes are used for the production of miniaturized parts, for drilling microholes, for shaping microgrooves and to achieve mirror-like superfinished surfaces.

Microturning makes use of very small, single crystal diamond tools with edge radii less than 1 μm (Figure 5). They are used for very small depths of cut, in machines that can reproduce movements with 5 nm positioning accuracy in different directions, and achieving roughnesses down to 50 nm. Actually this is problematic with ferrous materials, but CBN tools are developed for this particular case. In Figure 6 (a) a micromilled mould made from H13 tool steel is illustrated, and in Figure 6 (b) moulded plastic parts compared to a ball pen point are shown.

Grinding is a process traditionally used for finishing operations, thus it is considered to be the most precise mechanical process. Nevertheless, in micromachining, grinding is not necessarily superior to other processes, but smooth surfaces of less than 10 nm peak to valley have been reported with this process.[23] Such smoothness can be realized either by grinding wheels with coarse abrasives mounted on high precision machine tools and with the use of accurate dressing

[21] N. Ikawa, R.R. Donaldson, R. Komanduri, W. König, P.A. McKeown, T. Moriwaki and I.F. Stowers, “Ultraprecision metal cutting—the past, the present and the future”. *Annals of the CIRP* **40/2** (1991) 587–594.

[22] G. Byrne, D. Dornfeld and B. Denkena, “Advancing cutting technology”. *Annals of the CIRP* **52/2** (2003) 483–507.

[23] L. Alting, F. Kimura, H.N. Hansen and G. Bissacco, “Micro engineering”. *Annals of the CIRP* **52/2** (2003) 635–657.

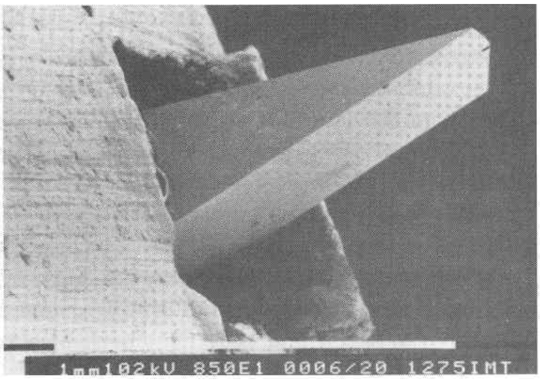
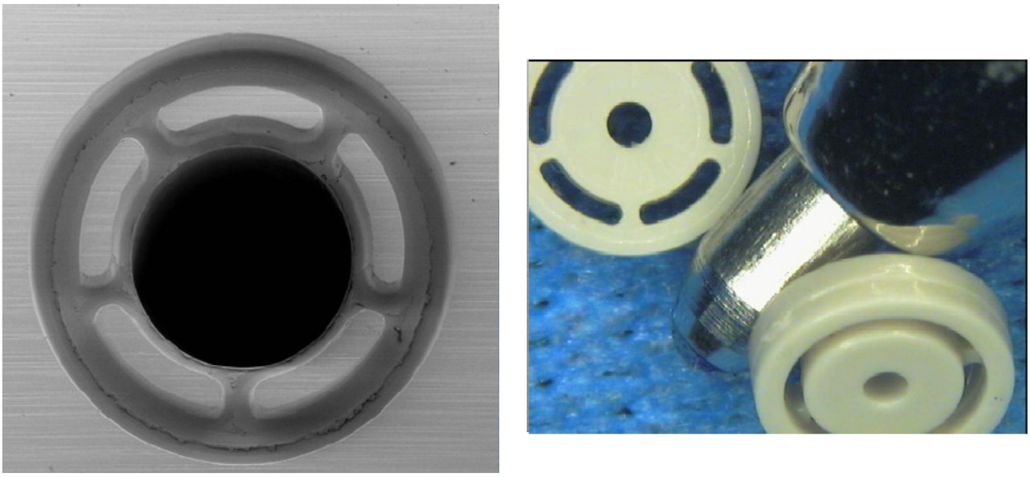


Figure 5. Single crystal diamond tool (scanning electron micrograph).



a b

Figure 6. (a) Micromilled mould made from tool steel H13 and (b) moulded plastic parts compared to a ball pen point (from H. Weule, V. Hüntrup and H. Tritschler, "Micro-cutting of steel to meet new requirements in miniaturization". *Annals of the CIRP* **50/1** (2001) 61–64).

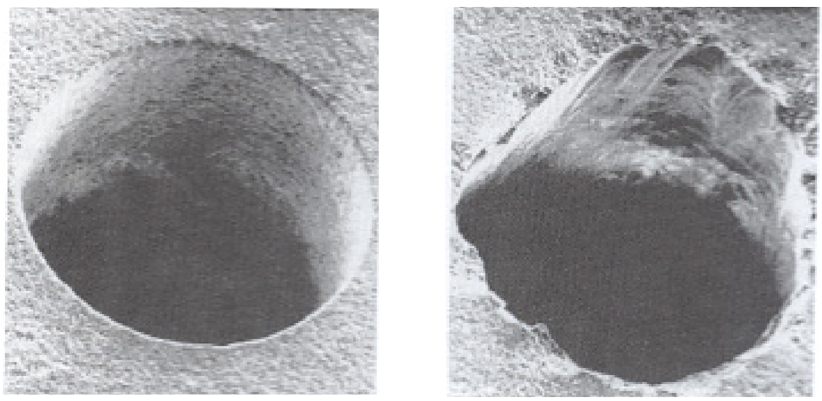
or by grinding wheels with fine abrasives (particles having sizes of about 10–20 nm). An abrasive process, referred to as nanogrinding, has been reported as yielding an average surface roughness of 1.14 nm for Al_2O_3-TiC and 0.79 nm for SiC, measured by atomic force microscopy.[25]

The advantages of the micromachining processes presented so far in this section are the very extensive knowledge that has been accumulated with their macroscopic precursors, the fact that they are relatively low-cost processes, and that they allow the manufacture of quite complex 3D structures. A wide variety of materials can be machined, including metals, plastics and their composites, since the electrical properties of the workpiece does not influence the

[25] H.H. Gatzen and J.C. Maetzig, "Nanogrinding". *Precision Engineering* **21** (1997) 134–139.

process, in contrast to the processes to be discussed in the following paragraphs. A typical application example is the drilling of microholes in laminated printed circuit boards. A disadvantage is the relatively high machining force, which limits machining accuracy due to deflexions of the tool and the workpiece.

Micro-ultrasonic machining (micro-USM) is another mechanical microprocess having its origins in a traditional macroscopic process. It employs a tool and a mixture of a fluid (water or oil) with abrasive particles. The tool is vibrated at ultrasonic frequency and drives the abrasive to create accurately shaped cavities on the surface of the workpiece. The shape and size of the cavities depend on those of the tool. In micro-USM, microtools and fine abrasives are used, with which ± 10 µm tolerance can be achieved. Since the tool does not exert any pressure on the workpiece the method is suitable for machining hard and brittle materials such as aluminum oxides, silicon and glass. Furthermore, the method is non-thermal and as a result it produces stress-free surfaces without defects attributed to heat-affected zones. In Figure 7 microholes drilled in alumina by (a) micro-USM and (b) laser beam machining are shown. It can be seen that the shape of the microhole is better defined in the former case while in the latter there are parts of the rim that have been affected by the heat of the beam. Micro-USM has low operating costs, the required operator skill level is modest and the production rates are relatively high. Technical problems are connected with the accuracy of tool holding and the response of the equipment itself to the ultrasonic vibration. In order to overcome the first problem, on-machine tool preparation has been introduced, in which the tool, before its preparation, is soldered to the machine head and then machined to the desired dimensions and shape. An approach to overcome the second problem is to apply the vibration to the workpiece instead of the tool.



a b

Figure 7. Scanning electron micrograph of microholes drilled in alumina by (a) micro-USM and (b) laser beam machining.

Abrasive Jet Machining (AJM) is an operation where grains, with sizes less than 100 µm, impinge with high velocity on the workpiece surface whose material is removed by the impacts. This method is used for making accurate shallow holes in electronic components, and, with the use of masks, patterns on semiconductors. The process is fast and the equipment inexpensive. Minimum feature sizes that can be made with this process are less than 50 μm.

FIB was described earlier as an ion beam lithography method. Recently, it has been suggested that it is suitable for producing microcomponents without the requirements of lithography. Sometimes FIB is considered as a thermomechanical process but it is more widely accepted as a solely mechanical technique in which the tool is replaced by a stream of energetic ions. The advantage of the method is that it can process very hard materials into peculiar shapes, but it is expensive and slow. A variation of FIB is Fast Atom Beam (FAB) machining where ionized atoms are accelerated to high speeds, neutralized and used as a mechanical cutting tool.

4.2 Electrothermal and thermal processes

In electrothermal and thermal processes thermal energy is provided by a heat source that is used to melt or vaporize the material to be removed. Machining forces are very small, and that permits the use of small and thin tools. The mechanical properties of the workpiece do not influence the machining process but thermal properties and in some cases electrical ones are important. In these processes it must be taken into consideration that because the tool is not in contact with the workpiece, uncertainties are introduced in specifying workpiece dimensions. Furthermore, heat affected zones (HAZ) may appear in the workpiece. Heat effects include resolidifying debris on the surface, and metallurgical transformations undergone by the layers just below the surface, which alter the properties of the material as a whole and may cause problems.

Electrical Discharge Machining (EDM) is the oldest and most-used operation of this kind. Micro-EDM is already widely used for micromachining. The workpiece (anode) and the tool (cathode) are submerged in a dielectric fluid and subjected to a high voltage. When the electrodes are separated by a small gap (whose dimensions can be precisely calculated) a pulsed discharge occurs. Sparks are generated and material is removed through local melting and evaporation. Both electrodes are worn away but the tool wear ratio varies depending on the tool material, and can reach values up to 70:1 for carbon electrodes. Because there is no contact between the electrodes, machining forces are negligible and the hardness of the workpiece is not critical, making the process eligible for machining conductive, hard and brittle materials. Machining of non-conductive ceramics is possible under certain conditions, but the method is still under development. Machining accuracy and repeatability of the process are good and the structures are burr-free, but the material removal rate is slow. By suitably adjusting process conditions surface roughnesses of 0.1 μm can be obtained, but the material removal rate is slower than if rougher surfaces are achieved.

Current micro-EDM technology can be categorized into four types. Sinker micro-EDM is performed as described above and is used for the fabrication of mirror image replicates of the tool on the workpiece. In micro-wire EDM a wire of diameter as small as 10 μm is used to cut through a conductive workpiece. This technique is used for producing microrods by rotating a cylindrical workpiece against the cutting wire. Micro-EDM milling is another variant, in which micro-electrodes 5–10 μm diameter are employed to produce cavities in a similar way to that of milling. Finally, micro-EDM drilling is a process where rotating microelectrodes are used as drills to create microholes in the workpiece. The holes can be 5–300 μm in diameter with depths up to 5 times the diameter, and can have a precision of ± 0.5 μm circularity. EDM and micro-EDM are well-established processes used for the production of moulds, extrusion dies, fuel injection nozzles, turbine blades, microholes, grooves, boreholes, complex 3D structures and convex shapes, and a lot of research is directed towards the improvement of the process and its applications.[26–28]

An important thermal technique is Electron Beam Machining (EBM). In this process, instead of electrical sparks high velocity electrons, travelling at about three quarters the speed of light, are used. The electrons are focused on an area on the surface of the workpiece and on impact their kinetic energy is converted into thermal, causing the workpiece material to melt and vaporize. The diameter of the beam is 10–200 μm, producing holes below 0.1 mm in diameter, with tolerances about 10% of the diameter and with a diameter-to-depth ratio of 1:10. With multiple pulses this ratio can be extended to 1:100. The process is performed in vacuum to prevent scattering of electrons by gas molecules of the atmosphere. Once the vacuum is established the process is extremely fast and is used for difficult-to-machine materials. A serious disadvantage of the method is its cost, which is high compared to other micro- and nanoprocesses.

Laser Beam Machining (LBM) is perhaps the most prominent process type presented in this section. LBM was introduced in industry for macroscopic cutting and welding of metals but lately is being used in micromachining as well. The importance of lasers in photolithography as uv sources was already discussed; here their application in ultraprecision material removal will be analysed. A thin laser beam is focused to a small spot on the surface of the workpiece and material is removed by ablation. The process is controlled by several parameters, including the light wavelength, others being spot size, beam intensity and depth of focus of the beam.

Laser wavelength λ is important because the minimum size of a feature that can be fabricated with light is about $\lambda/2$, as pointed out in section 3.1. The spot size, i.e. the minimum diameter of the focused laser beam, also depends on the wavelength. It is generally accepted that for wavelengths shorter than 200 nm direct photochemical bond breaking plays an important rôle in ablation. Laser types currently used in micromachining are solid state lasers, such as Nd-YAG and Ti-sapphire lasers with wavelengths of 1.064 μm and 775 nm respectively, and gas lasers, such as CO_2 ($\lambda = 10.6$ μm) and excimer lasers. Excimer (a contraction of EXCIted diMER) lasers are pulsed lasers driven by a fast electrical discharge in a high-pressure mixture of a rare and a halogen gas. Available wavelengths are 353 nm (XeF), 308 nm (XeCl), 248 nm (KrF), 193 nm (AF), 157 nm (F_2) and several years of research and continuous improvement has

[26] D.T. Pham, S.S. Dimov, S. Bigot, A. Ivanov and K. Popov, "Micro-EDM—recent developments and research issues". *Journal of Materials Processing Technology* **149** (2004) 50–57.

[27] Z. Wang, Y. Zhang and W. Zhao, " Study on key technologies of micro-EDM equipment". Proc. 4th Euspen International Conference, Glasgow, Scotland, pp. 51–52, May–June 2004.

[28] J. Fleischer, T. Masuzawa, J. Schmidt and M. Knoll, " New applications for micro-EDM". *Journal of Materials Processing Technology* **149** (2004) 246–249.

enabled them to be successfully applied in ultraprecision processes, especially for the fabrication of very complex 3D structures.[29,30] These lasers are more advantageous than other lasers because the wavelengths are more compatible with micromachining and they produce less thermal damage, see also Figure 7 (b). In Figure 8 a human hair machined by an excimer laser is illustrated. This figure demonstrates not only the structure forming capabilities of the process but also that even a delicate material such as hair shows no apparent damage after the process. It should be noted that typical powers for these lasers range from 3 to 50 MW (with pulses lasting a few tens of ns), with which almost all metals can be machined.

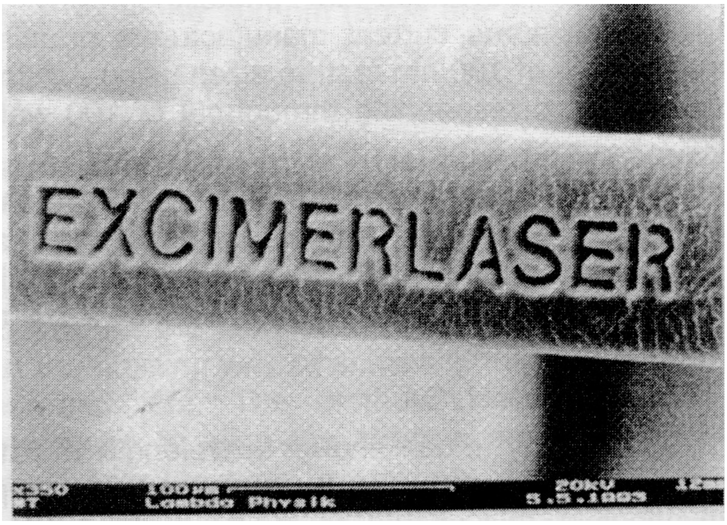


Figure 8. Human hair engraved with an excimer laser (from J. Corbett, P.A. McKeown, G.N. Peggs and R. Whatmore, "Nanotechnology: international developments and emerging products". *Annals of the CIRP* **49/2** (2000) 523–545).

Based on pulse length three operation modes can be specified: long, short and ultrashort. In long mode the pulse duration is greater than 0.25 ns and is of limited use in micromachining mainly due to the generation of deleterions HAZ: heat diffuses to the surrounding material causing undesired results. Short pulses last no longer than 10 ps, and ultrashort pulses are a million times shorter than nanosecond pulses and include the so-called femtosecond lasers. Femtosecond lasers have peak powers of 5–10 GW, powers that no material can withstand. This means that they can be utilized for the processing of metals, ceramics, glass, polymers, semiconductors, including very hard materials, even diamond, and materials with high melting points, such as molybdenum. Another advantage of machining with femtosecond lasers is that

[29] N.H. Rizvi and P. Apte, "Developments in laser micro-machining techniques". *Journal of Materials Processing Technology* **127** (2002) 206–210.
[30] K.H. Choi, J. Meijer, T. Masuzawa and D.H. Kim, "Excimer laser micromachining for 3D microstructure". *Journal of Materials Processing Technology* **149** (2004) 561–566.

there is no damage to the material because the duration of the laser pulse is shorter than the heat diffusion rate. This increases the efficiency of the process and is beneficial for the obtainable precision of the machining.[31]

4.3 Electrochemical processes

In this subsection electrochemical energy is involved in the material removal or forming operations. Additive techniques and the main processes for the production of porous Si are also included here. The most popular processes are electrochemical machining (ECM) and electrochemical grinding (ECG). ECM involves a cathodic electrode and an anodic workpiece which are separated by a highly conductive electrolyte. When current is applied material removal is accomplished. Like in EDM and USM the shape of the tool electrode defines the shape obtained on the workpiece. ECM is suitable for micromachining because removal is achieved virtually atom by atom. In ECG a conductive abrasive wheel is used as cathode and material is removed both electrochemically and by abrasive action.

Machining with ECM results in very smooth surfaces. Metals, regardless of their physical properties, especially their hardness, can be machined as in EDM. Compared to the latter, ECM has the advantage that no HAZ are created, and there is almost no tool wear. Other advantages are the low running costs, the by-production of very little scrap, and the ease of automation of the operation, while machining time is comparable to that of EDM. Furthermore, no residual stresses form and it is a burr-free process, also used for deburring machined components. Disadvantages of the method are the initial cost of the equipment and the fact that dissolution of the material occurs over larger areas than those facing the electrode. Electrochemical processes, despite their advantages, are not used in the IC industry, because in this particular field the so-called "dry processes" are preferred. Generally speaking, non-lithography based processes are of limited application in the IC industry due to the reasons explained in the following paragraphs, but extremely useful in other areas of application.

5. Nanofabrication methods

This section is dedicated to methods that are used for manipulating matter atom by atom in order to fabricate stable structures at the nanometre scale. This "bottom-up" approach, where instead of subtracting matter, atoms are placed in prescribed positions to form a complicated, functional structure, is somewhat different from the methods described so far. Some scientists have even envisaged the fabrication of nanomechanical components consisting of atoms, like the planetary gear in Figure 9. Molecular nanotechnology, as this approach is called, became known through the pioneering work of K.E. Drexler, who has worked on establishing its basic concepts and describing manufacturing systems able to produce components and devices of molecular size.[32]

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[31] J. Meijer, K. Du, A. Gillner, D. Hoffman, V.S. Kovalenko, T. Masuzawa and A. Ostendorf, "Laser machining by short and ultrashort pulses". *Annals of the CIRP* **51/2** (2002) 531–549.

[32] K.E. Drexler, *Nanosystems: Molecular Machinery, Manufacturing and Computation*. New York: Wiley (1992).

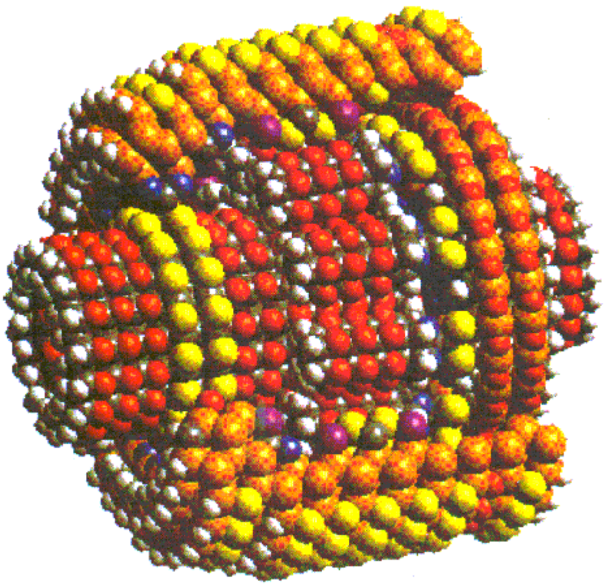

Figure 9. Computer simulation of a molecular planetary gear.

Two instruments, the scanning tunnelling microscope (STM) and the atomic force microscope (AFM), are used to fabricate surface structures with dimensions from less than 100 nm to atomic dimensions. The STM was developed in the laboratories of IBM in Zürich and originally it was built for studying the topography of material surfaces at the atomic level. Its inventors, who won the Nobel Prize in 1986 for their work, were able not only to measure and image surfaces at the molecular scale, but also to manipulate atoms and place them in designated positions. With this instrument 35 xenon atoms could be arranged on a nickel substrate, spelling out 'IBM' (Figure 10). AFM is a related instrument capable of producing 3D images of any surface, whereas the STM is only useful with conducting surfaces. Since their invention, about 20 years ago now, these instruments have added considerably to nanotechnology research but also have numerous applications in metrology, electronics, data storage and many other fields.[33]

6. Applications

In this section, applications of micro and nanoprocesses are briefly considered. Lithographic processes are already deeply embedded in manufacturing in many fields of science and engineering, and especially in the IC industry. The other processes, although little used in the IC field, are preferred for the commercial production of e.g. computer hard disks, ink-jet printer nozzles, mirrors, lenses, compact disk reader heads, photocopier drums, telecommunications devices, MEMS and many others, exploiting the very small sizes and excellent surface finishes

[33] T.V. Vorburger, J.A. Dagata, G. Wilkening and K. Iizuka, " Industrial uses of STM and AFM". *Annals of the CIRP* **46/2** (1997) 597–620.

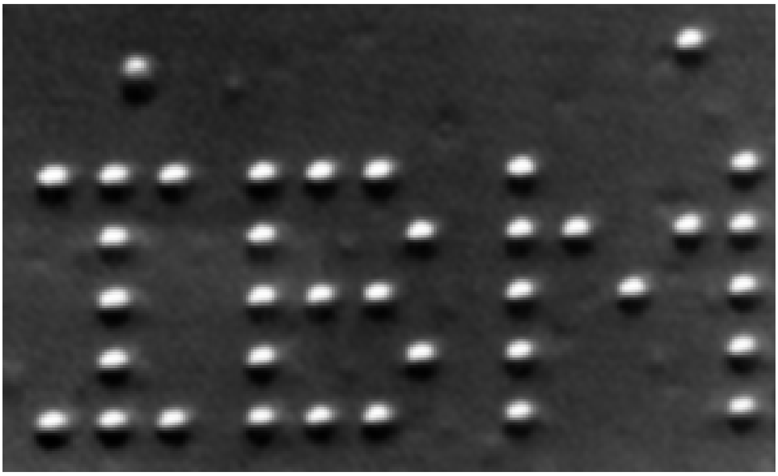

Figure 10. The IBM logo created from 35 xenon atoms.

that can be achieved and the wide selection of materials and geometrical characteristics that can be handled. The preference for lithography techniques for ICs is dictated by both technical and economical reasons, since ICs require the manufacturing of very small features and batch fabrication techniques. On the other hand, devices such as MEMS, which are made for very specific purposes, are produced in low volumes and typically use non-IC materials. For such devices, for which low cost is not as important as for e.g. computer chips, other processes may be useful.

As pointed out before the number of individual electronic components in a microprocessor has increased from 20000 transistors in 1980 to hundreds of millions on the latest silicon chips, with concomitant increases in computer power and memory. Chip structures have become more compact and the large number of transistors has allowed computer speeds to increase. Data storage is another important area of application. Data storage devices need to be smaller and one way to achieve this is to write and read data at higher density. The AFM method is suitable for such a task. In a process similar to the operation of the phonograph, the scanning tip of an AFM is heated and then makes contact with a disk. The tip, whose trace is about 40 Å, "burns" and writes the data on the plastic material of the disk. Data reading is performed by bringing an AFM tip into contact with an already written disk. With this method, readable data storage with a density of 400–500 Gb/in^2 can be achieved, which is quite an accomplishment if one considers that conventional magnetic data storage devices have densities of 20–50 Gb/in^2. Such AFM-based data storage devices are now being studied at IBM, with especial regard to control of contamination of the material during its production and processing. Their small size will enable them to be used in watches, cellular telephones, laptop computers etc., whilst their high-density data storage capability will lead to terabit data storage systems on 2.5 inch hard disks.

The modern automotive industry extensively incorporates electronic devices into cars. These devices are mainly miniaturized sensors. Pressure sensors, fuel and air flow control systems, gyroscopes, accelerometers and microactuators are some of the current devices in automotive applications. They result in increased car performance and safety. Miniaturization results in reduced component cost. Typical examples are the airbag accelerometers that help to protect the driver from being injured in severe crashes, anti-skid and roll-over systems, and intelligent sensors for efficient engine control. The shrinkage of electronic systems (as well as the associated engineering components) has led to significant reduction of the size and weight of car systems. A typical example is the ABS for braking, whose weight has been reduced from 6.2 to 1.8 kg, according to Bosch, from 1989 to 2001. Note that several car parts must now be ultraprecision machined in order to be functional.

In space applications, the trend towards miniaturization is probably greater than in any other field. Demand for small satellites orbiting the earth has increased over the past few years, due to growth in communications. The internet, mobile telephones, television stations and other applications all require satellites. Companies are trying to make them smaller because they are then easier to put into and maintain in orbit, and cause minimal pollution when going out of order. Space agencies are developing small space probes able to travel to other planets.

Medical applications are legion and very important for the improvement of the quality of life. They include prosthetic implants and surgical tools that are ultraprecision finished, and diagnostic devices small enough to enter the body of a patient. Another area is the development of nanostructured drug delivery particles, with selectively reactive molecular coatings that will act in specific places inside the human body.

7. Conclusions

In this paper the micro- and nanoprocesses used today and considered to have the potential to play a major rôle in tomorrow's microfabrication have been presented. Both lithography and non-lithography-based processes have been considered and their main characteristics have been described and compared. Furthermore, some nanofabrication methods have been discussed. Finally, some current and potential uses of these processes have been analysed to show their importance in today's industry and life.

Even though the impact of nanotechnology is already great, expectations for tomorrow are even greater, since it will make communication, transportation, data storage, health treatment and many other technological applications faster, safer and cheaper. The benefits of such advanced products and applications in many technological areas will be significant and the fields to which they will be applied will lead to a new era. International interest is greatly increasing and leads to a concomitantly growing research activity, in the very vanguard of modern science and technology.

Abbreviations

AFM: the atomic force microscope
AJM: Abrasive Jet Machining
CBN: Cubic Boron Nitride
DIBL: Deep Ion Beam Lithography
EBL: Electron Beam Lithography

EBM: Electron Beam Machining
ECG: electrochemical grinding
ECM: electrochemical machining
EDM: Electrical Discharge Machining
EUVL: Extreme UV Lithography
FAB: Fast Atom Beam
FIB: Focused Ion Beam
GTM: grey-tone masks
HAZ: heat affected zones
LBM: Laser Beam Machining
IBL: Ion Beam Lithography
IC: integrated circuit
IPL: Ion Projection Lithography
LIGA: an acronym or Lithographie, Galvanoformung und Abformung
MEMS: microelectromechanical systems
Micro-EDM: micro-Electrical Discharge Machining
Micro-USM: micro-ultrasonic machining
NGL: Next Generation Lithographies
PSM: phase-shifting masks
RET: resolution enhancement technologies
SCALPEL: SCattering with Angular Limitation Projection Electron beam Lithography
STM: scanning tunnelling microscope
uv: ultraviolet
3D: three dimensional