N. P. Mahalik

Micromanufacturing and Nanotechnology

With 300 Figures

Springer
Dedicated to all my

TEACHERS

Especially to

Sri Abhimanyu Mahalik
Smt Jayanti Mahalik
Er Babuchand Mahalik
Sri Prabhakar Barik
Professor P R Moore
Professor S K Lee

and last but not the least

Sri Tathagata Satapathy
(MP – Dhenkanal; Editor – The Dharitri)
Sophisticated miniaturised components and systems may indeed change all kinds of products and equipment in the most dramatic way. Methodology and design of miniaturisation represent a broad research topic with applications in fundamental physics, chemistry, martial science, computing methods, ultra-precision engineering, fabrication technology, micromaching, and many others based on the principles, characterization, modeling, simulation, sophistication, flexibility of state-of-the-art technology. Micromanufacturing and Nanotechnology (MaN), an advanced product and equipment design concept has emerged and caters to the need for miniaturisation. Technological research in the field of MaN is now expanding; its design phases appear to be highly complex and involve multi-physics and interdisciplinary approaches. The main objective of this book is to provide information on concepts, principles, characteristics, applications, latest technological developments and comparisons with regard to micro/nanosystems and technology. It incorporates research, development, tutorials and case studies. Academic and industrial research and developments in microengineering, micromanufacturing, micromechanics and nanotechnology are being carried out at many different institutions around the world. The technological trend in this domain (e.g., design and development methodology, current application scenarios, pros and cons, etc.) needs to be disseminated extensively so that the MaN revolution can spread to serve society. In particular, the book is intended to focus on describing the implicit concept of micromanufacturing and nanotechnology, multi-physical principle of microelectromechanical systems (MEMS) and micro-opto-electro-mechanical systems (MOEMS), design tips and hints, as much as the techniques and methodology.

Micromanufacturing and nanotechnology are two sides of a coin. There has been confusion and arguments on the terms microengineering, microsystems, ultra-precision engineering, micromachining, nanofinishing, micromechanics, microstructures and Microsystems. The authors of the Chapters have attempted to clarify this confusion. The book will undoubtedly enable the readers to understand the underlying technology, philosophy, concepts, ideas, and principles, with regard to broader areas of micromanufacturing and nanotechnology such as application of laser technology, lithography, bulk and surface micromachining, nanofinishing, error compensation, MEMS, MOEMS, carbon nanotubes, micro energy chemical system, fuel cell, microstructure for space propulsion, biosensor, etc. Aspects of microsystems in terms of design process, practice, techniques, platforms, and experimental results have been presented in proper order. The
chapters include topical and general description as far as current research and technological developments are concerned. Fundamental methods, initiatives, significant research results as well as references for further study have been presented. Relative merits and demerits are described at the appropriate places so that novices as well as advanced practitioners can use the evaluation to guide their choices. All the contributions have been reviewed, edited, processed and placed appropriately in order to maintain consistency so that irrespective of whether the reader is an advanced practitioner or a new comer he or she can get most out of it. Since this book covers many aspects of interdisciplinary subjects, the importance of the book within the micro and nano domain is considered significant. The roadmap of the book is as follows.

Chapter 1 is a general introduction. Chapter 2 presents the principles of MEMS and MOEMS. Very precise definitions of different physical phenomena and their utilisation with respect to MEMS and MOEMS have been presented. Chapter 3 presents fundamental principles of application of laser technology in micromanufacturing. Geometrical compensation of high precision machine system is of paramount importance. Chapter 4 highlights the basic principle and experimental architecture of computer assisted laser interferometer based method for achieving compensation of errors. In this chapter the model of error and procedural method of its compensation is described. Chapter 5 discusses about the bulk micromachining processes, a fundamental process requirement for microsystems and equipment manufacturing. A step forward to this process is considered as surface micromachining. Chapter 6 adheres the principle of surface micromanufacturing. Chapter 7 discusses latest developments on microsystem conformant OVD (Optically Variable Device), a very demanding device that has long been used for document security applications. Various types of nanofinishing techniques, the important method in manipulating and describing not only micro-but the macrosystems are described in the Chapter 8. The role of micro- and nanotechnology in space applications is presented in Chapter 9. Carbon nanotubes and nanostructures are introduced in Chapter 10 and 11. It has been variously that the future of the computing world will be based on molecular computing. A comprehensive description of molecular logic gates based on fluorescence, absorption and electronic conductance is presented in Chapter 12. Chapter 13 provides some research outcome with regard to the design of microscale cantilever devices that can act as biological sensors. Transportation of micro-energy through microdevices is a challenging breakthrough and is referred to as MECS (Micro Energy and Chemical Systems). Potential applications are microelectronic cooling systems, chemical reactors, fuel processing and heat pumps as outlined in Chapter 14. Next, a detailed description of sculptured thin films is provided. The following two chapters discuss e-beam and optical nanolithography techniques, respectively. Chapter 18 provides some phenomenological description of nanotechnology vis-à-vis fuel cell applications. Derivatisation of carbon nanotubes with amine and chemical crosslinking in C_{60} thin films are presented in Chapter 19 and 20, respectively.

The success story of this book ‘Micromanufacturing and Nanotechnology’ is in fact due to the direct and indirect involvement of many researchers, advisors,
technocrats, academicians, developers, integrators, designers, and last but not the least the well-wishers. Therefore, the editor and hence the publisher acknowledge the potential authors and companies whose papers, reports, articles, notes, study materials, etc. have been referred in this book. Further, many of the authors of the respective chapters gracefully acknowledge their funding agencies, without which their research could not have been completed. In particular persons such as M. Adrian Michalicek, Wassanai Wattanutchariya, Kannachai Kanlayasiri, Joseph Thomas, Hadi Hasan, Nitin Sharma, Patrick Kwon, Sharee McNab, David Melville, Conrad Wolf, Andrew Thompson, Alan Wright, Helen Devereux, Gary Turner and Mike Flaws and the following agencies, institutes, companies and journals are acknowledged.

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1 Introduction

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1.1 Background

In the year 1959, Feynman proposed the possibility of manufacturing ultraminiaturised systems for a variety of applications, to a level that may engross multiscale formulation methods involving the manipulation of molecules and atoms. Fundamental technological research and development in this domain has been underway since then. Arguably, with regards to past developments, it can be stated that the research and developmental activities broadly fall under the four major categories: precision engineering, ultra-precision engineering, micromanufacturing, and nanotechnology. The scope of research in the first three categories is vast and considered to be discipline dependent. For instance, while the methodological principles of precision engineering and ultra-precision engineering are more closely related to mechanical machining and processes, micromanufacturing in a generalised sense, is applied for producing VLSI-related products and systems. Though recently its scope has been broadened, apparently advocating the interdisciplinary scenario because of the dramatic emergence of MEMS (Microelectromechanical Systems) and MOEMS (Micro-opto-electromechanical Systems) technology. On the other hand, nanotechnology is viewed as a truly interdisciplinary domain accommodating several disciplines including general science. It is not our concern to describe the topical subjects of all these major domains, however at this point it suffices to say that one of the objectives of all these technological advancements is being focused on manufacture and design of miniaturised systems or products that can solve the humane expectations. Many industries in conjunction with academic institutions and R&D sectors are active in this multiphysics-multiengineering sector so that the manufacturing of smaller parts, components, products and systems at the level of micro/nanoscale with more functionalities and capabilities can easily be realised. To some extent this chapter attempts to introduce a road map to the concept of micromanufacturing and nanotechnology, which is being reflected in
the following chapters in more detail. Definitions of commonly used terminology will be provided, where necessary.

1.2 Introduction

Manufacturing is the cornerstone of many industrial activities and significantly contributes toward the economic growth of a nation. Generally, the higher the level of manufacturing activity in a country, the better is the standard of living of its citizens. Manufacturing is the process of making large quantities of products by effectively utilizing the raw materials. It is a multidisciplinary design activity simply involving the synergistic integration of production and mechatronics engineering. The products vary greatly from application to application and are prepared through various processes. It encompasses the design and production of goods and systems, using various production principles, methodologies and techniques. The concept is hierarchical in nature in the sense that it inherits a cascade behaviour in which the manufactured product itself can be used to make other products or items. The manufacturing process may produce discrete or continuous products. In general, discrete products mean individual parts or pieces such as nails, gears, steel balls, beverage cans, and engine blocks, for example. Conversely, examples of continuous products are spools of wires, hoses, metal sheets, plastic sheets, tubes, and pipes. Continuous products may be cut into individual pieces and become discrete parts. The scope of manufacturing technology includes the following broad topics:

- Precision engineering and ultra-precision engineering
- Micromanufacturing (Microelectronics and MEMS)
- Nanotechnology

1.2.1 Precision Engineering

The technical field of precision engineering has expanded over the past 25 years. In 1933, the Precision Engineering Society was established in Japan and soon thereafter the activities were accelerated due to new impetus from Europe. The first issue of the journal Precision Engineering appeared in 1979 and the first academic program began in 1982 (Source: American Society of Precision Engineering (ASPE)). According to ASPE, “…precision engineering is dedicated to the continual pursuit of the next decimal place.” Precision engineering includes design methodology, uncertainty analysis, metrology, calibration, error compensation, controls, actuators and sensors design. A more complete list is given below (www.aspe.net).

- Controls
- Dimensional metrology and surface metrology
Frequently used terms within the domain of precision and ultra-precision engineering are precision processes, scaling, accuracy, resolution and repeatability. The precision process is a concept of design, fabrication, and testing where variations in product parameters are caused by logical scientific occurrences. Identification of these logical phenomena and strategically controlling them is very fundamental to precision manufacturing. Scaling is a parameter that defines the ratio attributes with respect to the prototype model. It is also considered as a fundamental attribute for predicting the behaviour of structures and systems for analysis and synthesis of miniaturised systems. Accuracy defines the quality of nearness to the true value. In the context of machine or production systems, accuracy is the ability to move to a desired position. As an example, if the actual value is 1.123 units and it is recorded as 1.1 units, we are precise to the first decimal place but inaccurate by 0.023 units. Resolution is the fineness of position precision that is attainable by a motion system. The smallest increment that is produced by a servo system is the resolution. There are two types of resolutions, electrical and mechanical. With regard to mechanical resolution, it is defined as the smallest increment that can be controlled by a motion system, i.e., the minimum actual mechanical increment. One can note that mechanical resolution is significantly coarser than that due to the involvement of friction, stiction, deflections, and so on. Repeatability is the variation in measurements obtained when one person takes multiple measurements using the same instruments and techniques. Repeatability is typically specified as the expected deviation, i.e., a repeatability of 1 part in 10,000 or 1:10,000, for example.

1.2.2 Micromilling and Microdrilling

Micromilling and microdrilling are two important processes of precision engineering. The micromilling process is considered versatile and facilitates creating three-dimensional miniaturised structures. The process is characterised by milling tools that are usually in the order of hundreds of micrometers in diameter. These tools are designed by the use of focused-ion beam machining process and are used in a specially designed, high-precision milling machine. The focused-ion beam machining process uses a sharp tungsten needle wetted with gallium metal. The tip of the needle is subjected to a 5-10 kV (sometimes higher) so as to enable the field ionization effect on the gallium. The gallium ions are then accelerated by the use of another energy source and focused into a spot of sub-micrometer order.
The kinetic energy acquired by the ions makes it possible to eject the atoms from the workpiece. This is referred to as a sputtering process. The sputtering yield varies inversely with the strength of the chemical bond in the materials. Either the movement of ions or the workpiece, depending upon the environmental conditions, can be controlled to obtain a wide variety of three-dimensional shapes and structures. It should be pointed out that the machining forces present in micromilling with tools of the order of micrometer diameters are dominated by contact pressure and friction between the tool cutting edges and the workpiece. As a rough calculation, one can note that in the focused-ion beam machining process, for a spot size of 0.45 \( \mu \text{m} \) with 2.5 nA of current, the required current density would be approximately 1.65 A/cm\(^2\). The micromilling process is applied for making micromolds and masks to aid in the development of microcomponents. Typically, a high milling rate of 0.65 \( \mu \text{m}^3/\text{nAs} \), corresponding to an average yield of 6.5 atoms/ion, can be obtained at 45 keV, 30° incidence, and 45 scans.

Microdrilling is characterised by the drilling of ultrafine holes. Drilling in the micro ranges, using the special microdrills, requires a precision microdrilling instrument. The end of the microdrill is called the chisel edge, which is indeed removed material cutting at a negative rake angle. Microdrills are made of either micrograin tungsten carbide or cobalt steel. Some coarse microdrilling machines are available that drill holes from the size of 0.03 mm in diameter to 0.50 mm in diameter, with increments of 0.01 mm. However, the present demand is for drills capable of drilling in the order of micrometers. An example of this is a sub-microdrilling technique utilising the phenomenon of ultrafast pulse laser interference. In this regard, for microdrilling and other delicate laser processing applications, Holo-Or Ltd. has released an optical element that creates an output spot in the form of a top hat circle with a diameter of 350 µm. The element accepts a collimated Gaussian incident beam with a diameter of 12 mm from a 10.6-µm CO\(_2\) laser. Smooth 300 nm holes were successfully drilled on a 1000-Å-thick gold film using the interfered laser beam, as compared to micrometer holes ablated using the conventional non-interfered laser beam. The most important parameters considered in microdrilling are: accuracy, sensitivity, quality and affordability. Some of the applications of microdrilling are given below:

- Air bearings and bushings
- EDM tooling
- Electronic components
- Gas and liquid flow
- Microwave components
- Nozzles
- Optical components

The major problem of conventional laser microdrilling is that the process has a short focal depth. It is known that this method typically achieves aspect ratios up to 100 in thick material, such as for a 15-µm hole in 1.5-mm-thick foil, for instance. This problem can be overcome by utilizing a Bessel beam. Deep high-
aspect ratio drilling is achieved due to the reason that the Bessel beam is non-diffracting and in practice they do not spread out. In the case of deep high-aspect ratio laser drilling, a pseudo-Bessel beam is generated using a pulsed laser. Some of the examples of microdrilling applications using a laser system developed by ATLASER di Andrea Tappi are presented in Table 1.1. The application of lasers to micromanufacturing has several advantages: noncontact processing, the capability of remote processing, automation, no tool wear and the possibility of machining hard and brittle materials.

Table 1.1. ATLASER di Andrea Tappi microdrilling system performance parameters (Courtesy: ATLASER di Andrea Tappi)

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
<th>Hole diameter</th>
<th>Hole pitch</th>
<th>Process time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si Wafer</td>
<td>0.54 mm</td>
<td>25 µm</td>
<td>50 µm</td>
<td>0.65 s</td>
</tr>
<tr>
<td>Silicon Carbide Wafer</td>
<td>0.64 mm</td>
<td>130x500 µm</td>
<td>130 µm</td>
<td>110 µm</td>
</tr>
<tr>
<td>Aluminum Nitride</td>
<td>425 µm</td>
<td>300 µm</td>
<td>290 µm</td>
<td>33 s</td>
</tr>
<tr>
<td>Cu-FR4 sandwich</td>
<td>0.5 mm</td>
<td>200 µm</td>
<td>3.3 s</td>
<td></td>
</tr>
<tr>
<td>Stainless Steel Sheet</td>
<td>120 µm</td>
<td>9 µm</td>
<td>50 µm</td>
<td>0.15 s</td>
</tr>
</tbody>
</table>

1.3 Microelectromechanical Systems (MEMS)

Microelectromechanical systems (MEMS) have already found significant applications in sectors that include, but are not limited to: automotive industry, aircraft industry, chemical industry, pharmaceuticals, manufacturing, defence, and
environmental monitoring. The relative merit for MEM systems lies in the fact that these components are fabricated by batch manufacturing methods similar to microelectronics techniques, which fulfills the added advantage of miniaturization, performance and integrability. The topical areas under MEMS are micromachining methods, microsensors and actuators, magnetic MEMS, RF MEMS, microfluidics, BioMEMS and MOEMS. The progress in microfabrication technologies is transforming the field of solid-state into MEMS. Micromachining is a process for the fabrication of MEMS devices and systems. Various energy transduction principles include thermal, magnetic, optical, electrical and mechanical. These are employed in designing the microsensors and actuators. Radio Frequency (RF) MEMS devices are mostly used in the field of wireless communication. Microfluidic MEMS devices handle and control small volumes of fluids in the order of nano and pico liter volumes. One popular application is a micronozzle for use in printing applications. MEMS technology has applications in the chemical industry, which gives rise to BioMEMS products. Surgical instruments, artificial organs, genomics, and drug discovery systems are based on BioMEMS products.

The miniaturised systems require less reagent, resulting in faster and more accurate systems. MEMS devices have better response times, faster analysis and diagnosis capabilities, better statistical results, and improved automation possibilities with a decreased risk and cost. Since most of the physical phenomenon and activations are to be measured and controlled precisely in a timely predictive manner so as to overcome realtime limitations, miniaturised components will have added advantages because of the inherent temporal behavior they possess. Moreover, prognostic measures in terms of sensor and actuator validation can be achieved through a system-on-a-chip (SOC) design approach. MEMS devices are useful for controlling micro mechanisms such as micromanipulators, micro-handling equipment, microgrippers, microrobot, and others, which are primarily used for clinical, industrial and space applications.

1.3.1 An Example: Microphenomenon in Electrophotography

Electrophotography can be used for a broad range of applications. These include:

- Manufacturing of PCB
- Creating images on a wide variety of receivers
- Thin coating on pharmaceutical tablets and capsules

Electrophotography produces documents and images. The ability to do so requires that micrometer-size marking, toner, and particles be precisely placed on a receiver by adopting micro level technology. In order to produce high quality electrophotographic images, it is necessary to carefully control the forces acting on the toner particles. These forces are predominantly either electrostatic or electrodynamic in nature. The precision in color electrophotography process is extraordinary. Color electrophotography is an advanced technique. It requires that
the separations comprising the subtractive primary images be precisely superimposed in order to create a sharp image with excellent color balance.

1.4 Microelectronics Fabrication Methods

One of the major inventions in the last century is microelectronics, called micro devices. Micro devices can be integrated circuits, which are fabricated in sub-micron dimensions and form the basis of all electronic products. Microelectronics design entails the accommodation of essential attributes of modern manufacturing. Fabrication technology, starting from computer assisted off-line design to real fabrication, deals with the processes for producing electronic circuits, solid structures, printing circuits as well as various electronic components, sub-systems and systems of subminiature size.

The design of an IC with millions of transistors and even more interconnections is not a trivial task. Before the real design is manufactured, the circuit is prepared and tested by using EDA (electronic design automation) tools. These tools help in synthesizing and simulating the behavior of the desired circuit by arranging the placement of transistors and interconnections within the chip area. These computer-assisted tools can also verify and validate all defects and conditions, respectively. The technology has been driven by the demands of the computer industry, space technology, the car industry and telecommunications.

The first step in fabrication is always the preparation of a set of photographic masks. The mask represents the features of the various elements and layers of the chip to be manufactured. This procedure is repeated several times to replicate the circuit. The mask appears on the surface of a thin silicon crystal wafer. A single wafer can accommodate several identical chips. Hence, the IC fabrication process is a batch-processing scheme. The preparation of masks can be carried out by the use of a computer-controlled electron beam to expose the photographic mask material in accordance with the desired configuration. The information is supplied to the computer in terms of a design data file.

Then three important fabrication sequences are followed on the wafer surface. These are photography followed by chemical, and thermal operations. This phase is called masking. The mask features are transferred to the wafer by exposing a light-sensitive photoresist coating through the transparent areas of the mask. The material areas of the wafer unprotected by the hardened photoresist are then removed by etching.

Etching techniques are characterised by their selectivity and degree of anisotropy. Etching can be either physical or chemical, or a combination of both. In order to develop active circuit elements such as transistors, n-type and p-type impurities are doped. Two commonly used doping methods are diffusion and ion implantation. Then a thin aluminum layer is deposited on the uppermost layers of the chip in order to allow metal to contact the device elements. The aluminum deposition is often achieved by using the chemical vapor deposition (CVD) method.
1.4.1 Bulk Micromachining

The term micromachining refers to the fabrication of micromechanical structures with the aid of etching techniques to remove part of the substrate or a thin film (Petersen, 1982). Silicon has excellent mechanical properties, making it an ideal material for machining. The fabrication processes fall into the two general categories of bulk micromachining and surface micromachining.

In general, the process uses the bulk material or substrate to form microstructures by etching directly into the bulk material. Bulk micromachining refers to etching through the wafer from the backside in order to form the desired structures. The structures are formed by wet chemical etching or by reactive ion etching (RIE). Usually, suspended microstructures are fabricated using wet chemical micromachining. The advantage of bulk micromachining and chemical etching is that substrate materials such as quartz and single crystal silicon are readily available and reasonably high aspect-ratio structures can be fabricated. It is also compatible to IC technologies, so electronics can be easily integrated. Disadvantages of bulk micromachining include pattern and structure sensitivity and pattern distortion due to different selective etch rates on different crystallographic planes (Bean 1978; Kern 1990; Danel and Delapierre 1991). Further, since both the front side and backside are used for processing, severe limits and constraints are encountered on the minimum feature size and minimum feature spacing.

1.4.2 Surface Micromachining

Surface micromachining is a process of fabrication of MEMS structures out of deposited thin films. The process is also employed for IC fabrication. It involves the formation of mechanical structures in thin films formed on the surface of the wafer. The thin film is primarily composed of three layers: low-pressure chemical-vapor-deposition polycrystalline silicon, silicon nitride, and silicon dioxides. They are deposited in sequence and subsequently selectively removed to build up a three-dimensional mechanical structure integrated with the electronics. The structure is essentially freed from the planar substrate. The process is very complex in the sense that it requires serious attention during the process, as the property of material significantly varies at the microstructure level. In particular, the following issues are dealt with cautiously (James 1998):

- Basic understanding and control of the material properties of thin films
- Fabrication features for hinged structures and high-aspect ratio devices
- Releasing method for the microstructure
- Packaging methods

Micromachining, using doped or undoped polysilicon as the structural material and silicon dioxide as the sacrificial material, is the most frequently used. Silicon nitride is used as an insulator. Hydrofluoric acid is used to dissolve the sacrificial
oxide during release. Primarily, the fabrication process involves the following steps:

- Substrate passivation and interconnection
- Sacrificial layer deposition and patterning
- Structural polysilicon deposition and doping
- Microstructure release, rinse, and dry

Some of the examples of polysilicon micromechanical devices are flexible suspensions, gear trains, turbines, cranks, tweezers, and linkages, which have already been fabricated on silicon. Although bulk micromachining is considered to be the older technology, the two developments (bulk and surface) ran parallel (French 1998).

1.5 Microinstrumentation

In order to achieve sophistication and improve availability, miniaturization technology based instrument design concepts are going to be adopted as the advanced instrumentation platform for most of scientific, industrial and academic studies. The topical research fields are material science for microstructures, microinstrumentation devices, transduction principles for microstructures, interfacing; integration, modeling, and performance issues. Microinstrumentation equipment is essentially useful where a higher QoS (Quality of Service) such as sensitivity, resolution, selectivity, fidelity, and repeatability is desired. Miniaturization improves portability, speed and spatial requirements. Miniaturization can help the engineer to measure and analyse the physical, chemical and biological parameters of an application where space and weight are limiting factors. A typical microspectrometer can take less space while satisfying the required capabilities to measure, analyse and provide precise signals for further analysis and processing. Microinstruments can be applied in nuclear reactors, space shuttles, research laboratories, and numerous other places. Other application fields include spectroscopy, surface analysis, tribology studies, topography, microfluidics, microtomography and imaging. Recently developed microinstrumentation equipment includes microoscilloscopes, a microvoltmeter and microradar. The principle of operation of such tools and equipment however, requiring the application of fundamental science and coherent and synergistic technological integration, is of paramount importance.

1.6 Micromechatronics

Mechatronics is a relatively new discipline, but has been firmly established. Technical areas such as motion control, robotics, automotive, intelligent control,
actuators and sensors, modeling and design, system integration, vibrations and noise control are studied under this topical subject. This macroscale interdisciplinary research area is considered as a synergistic integration of mechanical engineering with electronics and intelligent control algorithms in the design and manufacture of products process. Micromechatronics deals with microscale machines. Microscale machines in turn incorporate MEMS architecture and methodology along with controls. The synergistic integration aspects with respect to microscale machines are not identical with regards to macroscale machines and systems.

1.7 Nanofinishing

In recent years, the structural modification and finishing methodology has attracted many researchers, system developers and integrators due to the fact that many mechanical and optical parts in the high-precision domain require precise structural perfection and manipulation on the nanometer scale. Nanomachining is a process that can provide advanced material shaping in this realm. Nanofinishing is a subset of the nanomachining process. Final finishing operations in the manufacturing of ultra-precision parts and components are always of concern owing to their physical, critical and controllable nature. In the domain of sophisticated miniature technology, deterministic high precision finishing methods are of utmost importance and are essential to the present micromanufacturing scenario. Proven finishing operations are:

- Grinding, honing and lapping
- Abrasive Flow Machining (AFM) with SiC abrasives
- Magnetic Abrasive finishing (MAF)
- Magnetic Float Polishing (MFP) with CeO$_2$
- Magnetorheological Finishing (MRF) with CeO$_2$
- Elastic Emission Machining (EEM) with ZrO$_2$ abrasives
- Ion Beam Machining (IBM)

It has been predicted that machining accuracies in conventional processes would reach 1 µm, while accuracies in precision and ultra-precision machining would reach 0.01 µm (10 nm) and 0.001 µm (1 nm), respectively.

1.8 Optically Variable Device

There has been a great deal of recent interest in optical security technology. Optically variable devices (OVD) are based on materials and technology that change appearance when viewed from different angles. OVDs are capable of producing sophisticated optical images with an exceptionally high level of security
features. The technique allows for the microprecision placement of pixels, which are forensically identifiable for maximum image clarity and security. Holographic technology, foil embossing equipment, application processes and information associated with security devices are the prime concerns in the adoption of these new security measures.

1.9 MECS

For many heat transfer applications, microchannel-based heat exchangers are being developed. The exchangers can be used for thermal management and waste heat recovery. The exchanger system should be compact and performance driven. Microscale combustion systems have been developed which take advantage of microchannel heat transfer to produce extremely compact, reliable, robust, portable and efficient high flux combustion systems. Recent developments have demonstrated heat fluxes several times greater than for conventional systems. This technology can be used within compact heating and cooling schemes or for compact power generation or propulsion. Micro Energy and Chemical System (MECS) is a recently developed concept and methodology, which can offer the required portability, mobility, compactness and flexibility. MECSs are microfluidic microdevices, capable of transferring enhanced rates of heat and mass in the embedded high surface-to-volume ratio microchannels of micro-scale geometries.

1.10 Space Micropropulsion

The application of micro and nanotechnology to the aerospace field requires a very interdisciplinary knowledge and engineering approach. Since the first concept of a nanosatellite to be manufactured on silicon wafers was proposed by The Aerospace Corp. in 1995, many research groups are on the way to produce and demonstrate such an invaluable idea. The building of nanosatellites is related to cost reduction. However, in practice, the space community is still waiting for the boom of the nanosatellite constellations, mainly because the enabling technologies are still not fully available or possibly because a different approach is necessary. Systems for aerospace applications require a sophisticated, one-off technology with more capabilities and functionalities as compared to similar terrestrial devices. This complicates the design or the selection of materials and requires a dedicated manufacturing process.