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NANOTECHNOLOGY - P. McKeown

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NANOTECHNOLOGY

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NANOTECHNOLOGY

1. Nanotechnology - what is it?

1.1 Introduction and definitions

Currently there is no single, internationally accepted, definition of nanotechnology. The journal *Nanotechnology* [1] which addresses itself exclusively to science and engineering at the nano scale, defines **nanotechnology** as "all those technologies and enabling technologies associated with either the top-down approach to fabricating miniature elements by sculpturing the desired structure from a microscopic piece of material as well as the bottom-up approach of building the desired structure molecule by molecule or atom by atom".

In Europe and the USA, the term 'nanotechnology' is frequently used to generally describe the science of atomic scale phenomena. However, the term '**nanoscience**' is better for work such as this which is aimed at gaining a basic understanding of atomic scale phenomena and processing. The manufacturing engineering community in the field of nanotechnology simply describes it as "design and manufacture of artefacts in the range of 100 nanometres (nm) to 0.1 nm", or adopts Taniguchi's [2] description, 'integrated systems of materials processing, dimensional measurement and positional control technologies which achieve nanometre accuracies, through sub-nanometre resolution, in-process feedback and feed forward control networks'.

Perhaps a more broadly accepted working definition is **"the study, development and processing of materials, devices and systems in which structure on a dimension of less than 100 nm is essential to obtain the required functional performance"**. This is the definition recommended by the authors of this paper; it covers nano-fabrication processes, the design, behaviour and modelling of nano structures, methods of measurement and characterisation at the nanometre scale and in particular:

- nano machining and nano fabrication techniques
- electronic device fabrication technologies
- scanning probe microscopes
- many aspects of microsystems technologies (MST)
- nano structured materials
- self organising and self assembling molecular structures
- biological and biomedical systems.

It is therefore clear that nanotechnology brings together engineering, physics, chemistry and biology. It includes materials processing through removal, accretion, surface transformation, joining and assembly right down to identification, manipulation and assembly of individual molecules. Many very high resolution techniques such as X-ray, electron beam and scanning probe microscopy etc. have been developed for the research of physical phenomena of matter at the sub nanometre and atomic scale. Through these physical techniques, analysis and even manipulation of structures at this scale have become possible. At the same time, whereas chemists have been traditionally involved in research and synthesis of small molecules, they now take a greater interest in building larger and more complex molecules. This has overlapped increasingly with research in biotechnology and thus biomedical engineering, leading overall to an increasingly interdisciplinary nature of research on the nanometre scale. It is primarily in this area that the term **nanoscience** is now frequently used to refer to current work where understanding molecular and atomic scale phenomena and establishing the science base at the nano scale is the current stage of achievement and where nanotechnology processes and products are the ultimate aim. Nanoscience can thus be envisaged as nanotechnology in its infancy; where working products are still far off. Examples include: supra molecular chemistry, the chemistry of nanostructured materials and mesoscopic physics e.g. where devices such as quantum wells (or dots) in which a single electron can be trapped and monitored might eventually lead to very fast, low energy quantum-computing.

1.2 What is a nanometre?

Nanotechnology, nanoscience and nanometrology all need the capability to measure and control motion to better than one nanometre in terms of displacement, size and profile. 'Nano' derives from the Greek *nanos,* a dwarf; i.e. very small.

A nanometre (1 nm) is 10^{-9} metres (10^{-9} m) - one billionth of a metre, approximately 80,000 times less than the diameter of an average human hair and 10 times the diameter of a hydrogen atom. Fig 1 shows some size scales from human to atomic. The metric dimensions relevant to high precision engineering, micro engineering and nanotechnology are:

1 millimetre (mm)	10^{-3} m	
1 micrometre (μm)	10^{-6} m	sometimes termed 'micron'
1 nanometre (nm)	10^{-9} m	
1 Angström Unit (Å)	10^{-10} m	
1 picometre (pm)	10^{-12} m	

Note:
- a normal human eye at closest focus can just resolve 20 μm
- visible light has a wave length between 0.4 μm (blue) and 0.65 μm (red)
- the atomic lattice spacing in silicon is 0.54 nm
- displacement measurement approaching picometre (0.001 nm) resolution can be achieved by X-ray interferometry and scanning tunnelling microscopy.

Fig. 1 here

1.3 The nanotechnology processes

Materials processing with nanometric resolution and control is applied to the measurement, manufacture and control of large, or 'macro' components such as optical or X-ray telescope mirrors, as well as in the fabrication of 'micro' features on very small artefacts such as integrated circuits. The inter relationships of nanotechnology and microsystems are addressed in Section 9.2; we recommend that micro and nano technologies are regarded as a continuum; they are highly interdependent.

Fig. 2 here

The ultra precision/nanotechnology processes, many of which are described in detail in this survey include:

- Single point diamond and CBN cutting (Fig. 3 shows a 1nm thick chip of copper made by diamond cutting);
- (Multi-point) fixed abrasive processes, e.g. diamond and CBN grinding, honing, belt polishing, including "ductile mode" micro-crack-free grinding of glasses and ceramics and other brittle materials (Fig. 4 shows the principle of ductile-mode cutting of materials);
- Free abrasive (erosion) processes, e.g. lapping, polishing, float polishing (mechano-chemical, chemo-mechanical processes);
- Chemical (corrosion) processes, e.g. etch-machining (perhaps as part of photo or electro-lithography);
- Biological processes, e.g. chemolithotrophic bacteria etch-processing of inorganic materials;

Figs 3 & 4 here

- Energy beam processes (removal, accretion and surface transformation processes), including:
  - photon^{X} (laser) beam: micro-cutting, drilling, transformation-hardening
  - electron beam^{X}: lithography, welding, micro and nano-drilling, (EBM) (Fig. 5 shows the principle behind electron beam machining while Fig. 6 shows text written with 4nm diameter e-beam cut holes)

Figs 5 & 6 here

  - electro-discharge^{X} (current) micro-machining (EDM)
  - electrochemical (current) machining (ECM)
  - LIGA deep etching using X-rays or excimer laser beams for lithography; then electro plating and moulding of micro components
  - inert ion beam^{X} machining (erosion) (focused (FIBM) and broad beam with mask) (Fig. 7 shows the principle behind ion beam machining while Fig. 8 shows the use of a gallium ion beam in repairing a Si chip, in comparison with laser cutting.)
  - reactive ion beam etching (RIE)

Figs 7 & 8 here

  - thin film techniques (Langmuir Bodgett) (LBTFT)
  - molecular beam epitaxy (accretion) (MBE)

- manufacture of nano phase powders and nanocomposites, liposome based structures etc.
- scanning probe microscopy (STM, AFM) for process engineering, enabling molecular manipulation, assembly and modification (Fig. 9 shows the principle of operation of an STM, Fig. 10 shows an STM surface scan of a graphite crystal showing individual carbon atoms and Fig. 11 shows how individual atoms can be manipulated on a surface by using STM).

x indicates the process is essentially electro thermal; for "atomic-bit" processing, high density energy in the range of 10^4 to 10^6 Joules/cm^3 is necessary.

Figs 9, 10, 11 here

1.4 The scope of this paper

The **aim and scope of this paper** is to explain what nanotechnology is, briefly trace its origins and recent historical development and then to describe the current state-of-the-art, in both the production of engineered artefacts and microbiological/biomedical fields. Ultra precision macro and micro machines are essential for success in nanotechnology for macro and micro components etc. Thus the paper also addresses the principles of design and control for ultra precision machines and instruments and gives some examples.

2. Nanotechnology - its origins and historical background

2.1 Precision Engineering

Manufacturing with higher precision is a development which has been gathering momentum over the last 200 years and accelerating over the last 25 years in terms of research, development, and application to product innovation. It has been driven by demands for **much higher performance of products, higher reliability, longer life** and **miniaturisation**. This development is widely known as **precision engineering** and today is generally understood as manufacturing to tolerances smaller than one part in 10^4 or perhaps 1 part in 10^5

The historical roots of precision engineering could be said to be horology, the development of chronometers and watches and, of course optics, e.g. the manufacture of mirrors and lenses for telescopes and microscopes. Major contributions were made to the development of high precision machine tools and instruments in the late 1800s and early 1900s by ruling engines for the manufacture of scales, reticules and spectrographic diffraction gratings. Today, ultra precision machine tools under computer control using single point or multi point diamond grinding wheels can position the tool relative to the workpiece to a resolution and positioning accuracy in the order of 1 nm. However, it will be noted from Fig. 2 that achievable "machining" accuracy includes the use of not only cutting tools and abrasive techniques but also energy beam processes such as ion beam and electron beam machining, plus scanning probe systems for surface measurement and molecular manipulation (pick-and-place).

So ultra precision manufacture has progressed through micrometre (μm) accuracy capability to enter the nanometre scale (**nano scale**) regime. However, this 'top-down' development has been joined by the prospects of 'bottom-up' nanotechnology such as the possibility of mobilising nano scale molecular structures to act as machines to guide and activate the synthesis of larger molecules, i.e. "**molecular nanotechnology**" with its promise of "building with atoms".

2.2 Taniguchi

The term **nanotechnology** was first introduced by Professor Norio Taniguchi formerly of Tokyo Science University, in 1974 at the International Conference on Production Engineering in Tokyo, sponsored by the International Institution for Production Engineering Research (CIRP) and the Japan Society for Precision Engineering (JSPE) [3]. Taniguchi used the word to describe ultra fine machining - the processing of a material to nano scale precision - work that he started in 1940 by studying the mechanisms of machining of hard and brittle materials such as quartz crystals, silicon and alumina ceramics, primarily by ultra-sonic machining. Subsequently he was in the forefront of research in using energy beam processes (EBM, FIB, RIE etc.) for fabrication of such materials to nanometric accuracies.

2.3 Feynmann

Although Taniguchi was the first to coin the term nanotechnology in 1974, it can be argued that the **concept of nanotechnology** was first enunciated by the American physicist Dr Richard Feynman (who became a Nobel Laureate in 1965) in his visionary lecture given to the annual meeting of the American Physical Society at the California Institute of Technology, Pasadena, California in December 1959. He entitled his talk "There's plenty of room at the bottom", [4]. At the outset he asked, "Why cannot we write the entire 24 volumes of the Encyclopaedia Britannica on the head of pin?". He pointed out that if you magnify the head of the pin by 25 thousand times, the area would then be equal to the area of all the pages of the Encyclopaedia Britannica, and went on to point out that all that was necessary was to reduce the size of all the writing in the encyclopaedia by 25 thousand times. He argued that the scanning electron microscope could be improved in resolution and stability to be able to "see" atoms and went on to predict the ability to arrange atoms the way we want them, within the bounds of chemical stability, to build tiny structures leading to molecular or atomic synthesis of materials. On all counts his predictions have been remarkably accurate, (see Fig. 6 for an example of electron beam writing). He did not use the term nanotechnology as such but accurately described its potential for extreme miniaturisation and the self organising and self assembly of molecules. It is on this concept of ."building with molecules". that the work of another American, K.E. Drexler has been developed.

2.4 Drexler

K. Eric Drexler was a student at MIT. He has become well known for "**molecular nanotechnology**", the concept of an all embracing manufacturing technology based on bottom-up molecular manufacture, popularised in his book "Engines of Creation" [5] first published in 1986. He postulated the possibility of mobilising nano scale molecular structures to act in a machine-like manner to guide and activate the synthesis of larger molecules. His ideas include billions of robotic type machines called "assemblers" which form the basis of a molecular manufacturing technology capable of building anything atom by atom and molecule by molecule.

Drexler's ideas gained greater publicity with the first designed protein produced at Du Pont in 1987 and then in 1990 the highly publicised manipulation of 35 xenon atoms by Eigler and Schweizer (Fig. 11), at IBM Research Division, Almaden, California using scanning tunnelling microscopy. The major research objectives of Drexler and his colleagues and followers in molecular manufacturing are based on designing a feasible assembler, modelling it computationally, and then building it. In 1995 Krummenacker and Lewis [6] implied that it may take 20 years of rigorous large scale research before such an advanced manufacturing technique using highly reactive molecules could become a reality. In the meantime many scientists and engineers remain somewhat sceptical about Drexler's ideas for molecular manufacture and referring to Drexler as a "futurologist", warn of the dangers in fuelling unrealistic expectations. However, the Foresight conferences on nanotechnology sponsored by Drexler and his colleagues have continued to grow in size and influence within the United States. Perhaps the best definition of Drexler's molecular nanotechnology is "**the projected ability to use potential control of chemical reactions to building complex materials and devices (including molecular machinery) resulting in precise control of the structure of matter at the molecular level**". The positive aspects of Drexler's publicity for nanotechnology include the encouragement of highly interdisciplinary research in the field and a much wider public awareness.

3. Nanotechnology - why is it important?

3.1 The opportunities of the "Nanometre Age"

Nanotechnology is a group of generic technologies that are becoming crucially important to many industrial fields and offering great promise of massive improvements to standards of living throughout the world. It is also a new way of thinking about possible solutions to problems currently obstructing new developments that can enhance the welfare of mankind. The Nanotechnology Tree (Fig. 12) shows in very general terms the wealth creating opportunities for the international business community which are arising from the science and engineering research base in micro systems technologies, nano science and nanotechnology. The main driving forces in this broad field from micro to nano systems are:

- new products that can work only on a very small scale or by virtue of ultra precision tolerances
- higher systems performance
- miniaturisation, motivated by "smaller, faster, cheaper"
- higher reliability, and
- lower cost.

Fig. 12 here

3.2 Nanostructured materials

Nanotechnology is already giving rise to a wide range of new and greatly improved **materials** for engineering, electronic, opto electronic, chemical, microbiological and biomedical applications. The term **nano-structured materials** usually refers to solids most of those in common use today being **microstructured**. Materials often behave very differently when **nano-structured**. The much finer grain size can produce denser materials with greatly improved mechanical properties perhaps three times better than the microstructured version. Thus aerospace and defence will benefit from much higher performance, e.g. light weight, high strength nano-composite materials and even ceramics. Stronger, improved life hip prostheses is just one of many benefits offered in the biomedical field.

Crystalline catalysts can exhibit better performance when in nano-structured form which also can improve conductivity useful for a variety of sensors/microsensors and energy conversion and storage applications. **Nanoparticles** and **nanopowders** which can be produced in suspensions (colloids), sol-gel and aerosols etc. offer a wide range of new and improved products. Smaller particles have larger active surfaces per unit of mass; this improves their chemical activity such as greater solubility in water. Stronger ceramics, more uniform and durable surfaces on porcelain and better inks for inkjet printing, are some benefits that derive from nanoparticle technologies. Buckminsterfullerine in the form of carbon C_{60} "buckeyballs" may prove to be a very effective nanoparticle dry lubricant in engineering applications. The "nanotube" version can perform as a mould for making nano-wires in suitable metals such as gold for electronic connectors and may be fabricated to form "molecular sieves" for faster and more selective filtration.

3.3 Thin films

Thin films or **mono layers** usually from 1 nm to 5 nm in thickness can be only one molecule or even one atom thick in some cases. They can be organic or inorganic and provide a wide range of excellent properties such as being chemically active in a useful way and being dense and hard for wear resistance. Monolayers, deposited on semi conducting substrates that emit electrons when sunlight falls on them are the basis of solar energy cells that can be expected to exhibit improved efficiency in the future. Thin layers can be deposited successively in different materials forming **multi layers** having for example, specific magnetic properties useful in magnetic recording with high packing densities; very many other useful properties are offered from high erosion resistance in hostile environments to the focusing of X-rays.

3.4 Nanofabrication

Nanofabrication covers a range of manufacturing processes that produce patterns and/or layers of material to form micro or **nano-structures**. The semiconductor/microelectronics industry has led the development and application of the photo- and electron beam lithography techniques which are the main basis for continuing miniaturisation in large scale production in the future. Ultra large scale integration (ULSI) chips that are smaller, faster, cheaper and with more memory will bring further massive improvements to the performance of micro processors, computers etc. and onwards to telecommunications, domestic, automotive and medical products and services. (Section 8 below, amplifies this topic.) However, microsystems technology (MST) products with micro mechanical features such as sensors or arrays of sensors and actuators fully integrated into the same (silicon) chip are already burgeoning; applications will expand in navigational, automotive, biomedical and pharmaceutical industries, e.g. the concept of the "laboratory on a chip" that may lead to entirely new ways to design and build pharmaceutical and industrial chemical plants with greatly improved quality control and efficiency (see sections 9 and 11 below).

3.5 Ultra precision machining

Ultra precision engineering and machining such as cutting, grinding and super finishing have been developed over the last thirty years to provide nano-precision surfaces on macro-components such as:

- ultra precision spindles - rolling element and hydro-dynamic gas or liquid bearings for next generation, higher performance magnetic memory disk file systems, high definition large scale projection television and video cassette recorders
- mirrors and lenses for optical systems operating primarily in the visible, ultra violet and X-ray wave-lengths; further advances in space communications, optical and X-ray astronomy, biomedical engineering etc. will be boosted by increasing accuracy and reducing the cost of the specialised machines and processes some examples of which are described in section 6.3 below.

3.6 Bio-medical applications of nanotechnology

This is a field that will, increasingly, be a major beneficiary of MST and nanotechnology developments; examples include:

- minimally invasive surgery, which is starting to be helped by remotely operated surgical instruments and diagnostic tools, e.g. micro-catheters down to 100 μm diameter incorporating optical fibres for delivery and retrieval of light images for high resolution cameras; nano-scale sensors for measuring blood chemistry. Incorporation of tip-mounted micro-turbine rotary cutters for arterial plaque removal is entirely feasible: cutters of this general type will also be useful for ophthalmic surgery.

- accurate and efficient drug targeting and delivery is made possible by nano-particle technology. Particles with specific surface topographies and selective reactive molecular coatings that already demonstrate a remarkable ability to arrive at targeted sites within mammalian bodies in enormously larger concentrations than normal, are being designed and tested. In effect, these medicinal 'bullets' coated with antibodies resist attack by the body's own defence cells and yet can lock on to the target cell such as a tumour, thereby avoiding the release of toxic drugs on to healthy tissue. Commercial availability of a range of such nano-particle drug delivery systems may emerge in the next 5 years (see section 11.4 below).
- many other biomedical applications currently the subject of R & D in Europe, Japan and the USA include:
    - replacement of damaged nerves by artificial equivalents
    - restoration of hearing or sight in some cases of damage or disease
    - improved adhesion growth of living tissue cells on to prosthetic implants by micro and nano surface patterning of implant materials, i.e. making more bio-compatible materials and surfaces.

3.7 Molecular nanotechnology

Molecular nanotechnology with the prospect of **'self assembly'** in which atoms, molecules, molecular aggregates organise and arrange themselves into ordered functioning entities without human intervention, such as organic monolayers, presents fascinating challenges and opportunities.

Steps have already been taken towards the "interfacing of molecules" by chemical activation of the probe and substrate that is to be built up or modified. Eventually and well into the future, self organising and self-assembly molecular systems that mimic the self assembly of molecules in biology, could well become a reality. Thus in what Rohrer refers to as the forthcoming 'Nanometre Age' [7] the massive, parallel operation of "bottom-up assembly" and self organisation of molecules will to some extent replace the "top down" miniaturisation philosophy of today's MST/MEMS and engineering nanotechnology. This chemistry/biochemical approach to nanotechnology is being led by Drexler and followers (see section 2.4 above; and section 11 below).

He wrote: "Assemblers will be able to make virtually anything from common materials, without labour, replacing smoking factories with systems as clean as forests. They will transform technology and the economy at their roots, opening up a new world of possibilities" [5]. Many regard this as highly futuristic and bordering on science fiction.

However before this, we can expect to see the emergence of experimental and then fully functional **"micro-factories"**, i.e. very small machines grouped within table-top dimensions for the manufacture of very small industrial products, such as micro-valves, pumps, electro magnetic/electro static motors and optical devices. Substantial space and energy savings together with reduced environmental pollution are the objectives of the Japanese NEDO, Micromachine Technology R & D Project for which an investment of US$ 200m is being made in the 10 year programme launched in 1991.

3.8 The global market for nanotechnology - brief summary

There can be no doubt that many new products will arise from today's nanoscience and nanotechnology R&D work in academia, research institutes and industry. Many existing macro products will be replaced by MST and nanotechnology products, produced by new nanotechnology based manufacturing facilities. Many estimates have been made for the size of the global market for "nanotechnology" products but it is impossible to reconcile and aggregate them accurately. Predictions include:

- a 1995 VDI report for the German Government estimates that by the year 2000 it will exceed US$ 250 bn [8].
- the market for MST/MEMS alone will exceed US$ 14 bn by 2000
- the market for 0.1 μm (100 nm) DRAMS will exceed US$100 bn also by 2000.

The following sections go into greater detail on the technologies, applications and prospective markets.

Nanotechnology is a major new technological force that will have substantial socio-economic effects throughout the world. Many benefits in standards of living and quality of life can be confidently expected.

4. Ultra-precision machines and instruments

4.1 Nano-precision processing machines

In order to use most of the nanotechnology manufacturing processes listed in section 1.3 above, ultra-precision machines and instruments are needed to control the three dimensional (3D) spatial relationship of the "tool" to the workpiece to accuracies in the order of 1 nm, 0.1 nm or even less. The tools can be:

- solid tools for cutting, abrasive or chemico-mechanical action
- energy beam tools
- scanning probe tools such as STM, AFM, magnetic, thermal or chemical-reactive probes etc.

Ultra-precision machine systems fall into three main classifications:

- large, computer numerical control (CNC) macro-machines for measuring, shaping or forming conventional macro-sized component parts; today, this can mean working to nano tolerances on macro-components
- instruments for metrological applications to macro and micro-components
- very small 'Feynman' machines ranging in size from a few millimetres down to micrometre dimensions.

In each case, there are eleven main principles and techniques that must be used in design and build to achieve under computer control, a **highly deterministic performance** as a sound basis for nano-precision capability.

4.2 Error reduction - the machine designer's guide to high precision

The Eleven Principles and Techniques for the design and manufacture of high precision machines and their control systems are now set out and briefly addressed. The 'Designer's Guide to High Precision' [9] [10] are essential steps in the process of '**error reduction**' of machines, and apply to conventional as well as ultra-precision machines:

(i) **MACHINE STRUCTURE** - the size of the loop between tool and workpiece should be as small as possible; this structural loop should be as resistant as possible to all disturbing agents; highly **symmetrical structures** can best achieve this; the structure should be made of materials that ensure long term secular stability, high static and dynamic stiffness (to resist internally and externally generated vibrational forces) and high damping (to rapidly attenuate any vibrational motions that do occur). Thus the structure must be as stiff or rigid as possible in its own right, mounted kinematically on three support 'feet' only and thus be geometrically unaffected by any distortional movements of the foundation on which it is mounted. It must exhibit the highest thermal stability i.e. be as geometrically insensitive as possible to internal or external temperature variations, for example, through the use of low expansion materials. Where temperature gradients exist, symmetry is very important. Seismic and acoustic isolation is essential for ultra precision machines. Other disturbing agents can include magnetic fields, humidity, atmospheric pressure and light e.g. radiation heating.

(ii) **KINEMATIC and SEMI KINEMATIC DESIGN** (first comprehensively enunciated by James Clerk Maxwell circa 1876) - machine elements should be designed as 'rigid' bodies and connected to mating elements with the minimum number of constraints needed for fixed location (6 constraints) or the required degrees of freedom (5 constraints for a linear or rotary motion); kinematic design practice offers high precision at lowest cost.

(iii) **ABBE alignment PRINCIPLE (or options)** - (enunciated by Ernst Abbe, Jena Germany circa 1890) - the line of action of the displacement measuring system must be co-linear with the displacement to be measured; the two options are that either the motion of an element such as a carriage must be free of all angular motion such as 'pitch' or 'yaw' or these angular motions must be measured in order to calculate and compensate for the consequences of the 'Abbe offset'.

(iv) **"DIRECT" DISPLACEMENT TRANSDUCERS** - the use of displacement measuring systems that are totally independent of disturbing agents such as drive mechanisms, e.g. lead screws; examples are scales and laser interferometers.

(v) **METROLOGY FRAMES** - a means of isolating the displacement measuring systems from machine structural distortion caused by motion of machine carriage elements, by mounting them on an independent, high stiffness framework geometrically related to the workpiece support datum.

(vi) **GUIDEWAY and ROTARY BEARINGS** - low limiting-friction, high 'averaging effect' bearings to provide high accuracy motion with low thermal effects and high damping; fluid film bearings such as hydrostatic air, oil or water are frequently used for macro-motions. Flexures in the form of monolithic linear or rotary spring mechanisms can be optimal for micro-motions.

(vii) **DRIVES** to carriages should be positioned to operate through 'axes-of-reaction' to ensure translation without rotational effects - or to achieve pure rotation with lowest radial, axial and 'tilt' error motions.

(viii)**THERMAL STABILITY** - it is essential to eliminate or minimise thermal inputs, external or internal, thus minimising thermal distortions and **'thermal drift'** of tool to the workpiece datum; it is achievable by use of low expansion materials, temperature controlled air or liquid passed over and/or through the machine or by servo error compensation, etc.

(ix) **SERVO DRIVES and CONTROL**

servo drives - high dynamic stiffness, high bandwidth, fast response; high speed dynamic position loop compensation to achieve zero following errors i.e. between actual and commanded position

CNC - high speed simultaneous control of all axes; 2D/3D systematic error compensation, refractive index compensation for laser interferometers and thermal drift error compensation are all essential capabilities for ultra precision control systems.

(x) **ERROR BUDGETTING** - essential at schematic design stage to ensure achievement of specified accuracy capability in an optimised manner:

- Geometrical : angular, e.g. pitch, yaw (Abbe) and roll, straightness and orthogonality error motions
- Thermal : loop expansions and distortions

(xi) **ERROR COMPENSATION** - CNC software error compensation - of systematic, quasi-static 2D or 3D error map values established by calibration; dynamic error compensation by use of fast tool servo drives; thermal error compensation by servo adjustment etc.

4.3 Error compensation through the control system

The eleven principles and techniques, are essential steps in **error reduction** of machines. However, powerful CNC systems incorporating the latest VLSI processors offer **software error compensation** capabilities (xi above) for high precision machines. A few, world-leading manufacturers now use the technique of software error compensation whereby the systematic errors in X, Y and Z at perhaps 64000 points in the 3D workzone of the machine can be greatly reduced and brought close to zero. Fig. 13 shows a 3D error map for a multi axis machine. The X, Y, Z systematic errors result from the inevitable geometric and deformation errors of machine structures and from guideways and displacement measuring systems etc. The intrinsic errors of the machine can usually be reduced by at least a factor of 10 by software error compensation.

Fig 13 here

4.4 The importance of dynamic stiffness

The dynamic loop stiffness of the machine is of utmost importance in achieving high accuracy, whether the 'tool' is one that generates intermittent disturbing forces such as a grinding wheel or is a virtually 'non-contacting' measuring probe such as used in a scanning tunnelling microscope (STM). As size reduces so the resonant frequency of the structure increases; its dynamic stiffness goes up and it can resist dynamic disturbing forces such as seismically and acoustically transmitted vibrations. Thermal expansion and thus thermally induced distortions of a structure also scale directly with size. So in these terms, the accuracy capability of a machine or instrument improves as it is made smaller. Thus micro-miniature machines typically of millimetre or even micrometre dimensions have excellent ultra precision potential. The first STM instruments could not achieve atomic resolution primarily because they were built essentially as macro-structures i.e. with low loop-stiffness between probe and the workpiece, so that seismic and acoustic vibrations caused them to oscillate with amplitudes much greater than atomic dimensions. Fig. 14 shows the small, compact but simple design of an early experimental STM that has very high resonant frequencies (26 KHz in the vertical Z direction). It can achieve atomic resolution with very little vibration isolation. Micro-miniature scanning probe devices can be fabricated onto silicon in a similar manner to VLSI circuits. These "**nano-fingertips**" can be used for micro or nano surface patterning either directly or by lithography (see section 7 below). In the future we can expect to see **miniaturised nano-tools** with thousands of tips which can recognise, extract and deposit molecules and atoms to build nano- devices such as sensors, actuators, complete nano-robots and other Feynman machines. Machines and instruments with nanometric resolution and accuracy are built today. Some examples on the macro scale are briefly described in sections 6.3 below.

Fig. 14 here

5. *Nanometrology*

For many products, the dimensional geometry of discrete components is crucial in determining quality of performance. Therefore, metrology, the science of measurement, the ability to measure with appropriate accuracy becomes important. **Accuracy** is defined, in the Oxford English Dictionary as "exact conformity with a standard or with truth". In metrology terms, accuracy is understood, according to the International Vocabulary of General Terms in Metrology, to be "the closeness of the agreement between the result of measurement and the (conventional) true value of the measurand" (measured quantity) [11]. In addition it is stated that the use of the term '**precision**'for accuracy should be avoided; precision is better understood as repeatability.

Nanometrology can be described as the science of measuring the dimensions of objects, or features on objects, to **uncertainties** in the order of 1 nm or better. The limit to **accuracy** is set by **uncertainty of measurement**. In practice it is the same thing. It is the size, shape and surface finish of parts, which ultimately determines functional performance, wear and fatigue life, ease of assembly etc.

Numerous measuring techniques are used to measure the dimensional characteristics of machined parts such as length, profile, eccentricity, surface roughness, etc.

5.1 Trends in metrological needs

The long term manufacturing trend for many strategic products, from automobiles to microchips, is for tolerances to be decreasing by up to a factor of three every ten years, as shown in Fig 15. According to Swyt [12] "between 1980 and 2000 state-of-the-art tolerances will decrease from 7.5 μm to 1 μm in the most demanding 'normal' machine tool based production, from 0.075 μm to 0.01 μm in the most demanding 'precision' production, e.g. diamond turning/grinding and from 0.005 μm (5 nm) to <0.001 μm (<1 nm) in the most demanding atom-, electron-, or x-ray machining based production". An issue which has to be addressed concerning this trend is the requirement to measure more accurately, and to reference and thus trace, these measurements to international (ISO) standards. Production control measurements are required to have an accuracy between 4 times and 10 times better than specified component tolerances, and, it is commonly accepted that reference standards should be between 4 and 10 times more accurate than the production control tolerances. Thus reference standards should be 16 to 100 times better than component manufacturing tolerances. As component tolerances reduce to sub μm values, then national standards laboratories face increasing challenges to satisfy industrial metrology demands e.g. see section 8.6, where true nano metrology is required for next generation ULSI circuits.

Fig. 15 here

5.2 Length and displacement measurement

In most measuring instruments or machines, size/length is measured by displacement of an appropriate fiducial sensor over the component. In nanometrology, instruments and machines have to incorporate linear displacement transducers with resolutions and accuracy in the order of 1 nm.

Fig 16 indicates the measurement accuracy limits for different physical principles [11]; it plots absolute measuring uncertainty i.e. accuracy against length of displacement for perhaps the most important linear displacement transducers in the field of nanotechnology, namely laser interferometry in the forms of Optical Heterodyne Interferometry (OHI) and Frequency Tracking Fabry Perot Etalon (FPE) together with X-ray Interferometry (XRI) all of which are capable of sub-nanometre resolution and accuracy. However FPE and XRI are limited in range to a maximum of 400 μm so far and are thus very restricted in nanometrology applications. However, it should be noted that the accuracy of all these systems is influenced and limited by other factors, such as linearity of output signals, robustness, stability, sensitivity against changes in working environment etc. All of these must be taken into account when specifying a measuring system for a measuring or production machine.

Fig. 16 here

Temperature variations, in particular, can have a major negative effect on repeatability and measuring accuracy of metrology systems. Manufacturing engineers are often unaware of the magnitude of errors caused by changes in the thermal environment; it is imperative that they become familiar with ways to minimise and to compensate for the whole range of thermally induced errors [10].

Laser interferometers i.e. OHI and optical scales (OS) are widely used for linear displacement measurements in ultra precision machines and instruments.

Modern optical grating scale systems with a 1 nm resolution and a range of 100 mm are currently available; this range is expected to increase to at least 500 mm soon. Current, commercially available, laser interferometer systems can be obtained with a 0.6 nm resolution and a range of several metres.

Thus the current relative accuracy applications of optical scales and laser interferometers can be said to be:

- Vacuum laser interferometry (OHI) can give the highest resolution and accuracy for large displacement measurement e.g. 0.1 nm over 1 m (Fig. 16).
- For accuracy requirements between 10 nm and 100 nm there is little to choose between scales and interferometers assuming they are calibrated properly.
- Scales are usually the preferred choice for accuracies between 0.1 μm and 10 μm. Their cost advantage usually makes them the appropriate choice for application to machine tools and coordinate measuring machines in the sub micrometre rather than the nanometric accuracy bandwidth.

For short ranges i.e. from a few micrometres to a millimetre or so, and if the range to resolution ratio is less than 2000 and the linearity is less than 0.1%, analogue transducers can be considered. These include linear variable displacement transformers (LVDT's), capacitance gauges, eddy current probes, etc., which are available with nanometric resolution. XRI and FPE techniques are expensive techniques to use in short range nanometrology applications but they can give near picometre resolution.

5.3 Surfaces - metrological characterisation

Knowledge of **surface topography** at the nanometre and increasingly at the atomic scale is important in understanding the functional performance of that surface. In addition, other surface properties such as chemical, magnetic, hardness, stress levels etc. are important for the same purpose. There are essentially two main methods of measuring surface topography i.e. surface form/profile, waviness and roughness; they are **stylus techniques** and **optical interferometry**.

In the conventional stylus method a diamond with a tip radius of typically 1 μm can achieve a profile height resolution of 1 nm and approaching 0.2 nm, based on a very high resolution LVDT. The **scanning probe microscopes** such as STM and AFM described in section 7 below, can achieve atomic resolution (Fig. 10).

The AFM is now being applied widely to the study of inorganic and organic surfaces e.g. the epitaxial growth of silicon layers for microelectronic applications and the study of biological molecules adsorbed on to surfaces.

Albert A. Michelson (1852-1931) developed the first optical interferometer system by exploiting a knowledge of optics, and how interference fringes are formed by light waves interfering with each other. He developed this concept of interference to measure displacement. Fig. 17 shows, schematically, the principal components of a modern optical interferometer system, namely an Optical Heterodyne Interferometer (OHI). Developments in modern electronics enable the use of optical interferometry for nano surface profile and roughness measurements. A commercially available system uses a piezoelectric transducer (PZT) to move a reference mirror, which results in the generation of a number of fringe patterns each time a measurement is taken. The movement of the PZT shifts the fringe pattern which is recorded by a detector and transferred to the system's computer.

Fig. 17 here

Fig. 18 shows an interferometric plot of a sub nanometre surface finish, measured with a commercially available system, namely 0.8 nm Ra obtained by ultra precision single point diamond turning of high purity optical germanium used for lenses in infra red night vision systems.

Optical techniques are limited by the amount of light which is reflected, or scattered off the test surface and returned through the microscope objective. However, their performance can be improved by the use of multiple-wavelength techniques, which enable the measurement of steep slopes, or steps up to a height of 15 μm in height.

Fig. 18 here

5.4 The Molecular Measuring Machine (M3)

Undoubtedly the most accurate 3D macro machine in the world at the time of writing is the Molecular Measuring Machine dubbed "M3" which has been developed at the USA's National Institute of Standards and Technology (NIST), [13]. This pioneering, world-leading project is aimed at imaging and measuring to nanometre accuracy, the positions of nanometre-size features located anywhere within an area of 50 mm x 50 mm and up to 100 μm high. This measuring machine, Fig. 19, is designed to meet the needs of industry working on next generation nano devices, particularly nano-electronics, ULSI (Ultra Large Scale Integration) circuits. It will provide calibration for the metrological standards by which to control the production of ULSI circuits with 100 nm line widths envisaged for widespread use within the next 20 years, e.g. line width standards and artefact standards for calibration of e-beam and x-ray production equipment etc.

Fig. 19 here

The maximum size of the specimen to be measured is 50 mm x 50 mm x 25 high; the vertical measuring range is 100 µm. It employs very high resolution scanning tunnelling and atomic force microscopes (STM and AFM). The target initial resolution of point-to-point measurement within the measuring volume was 0.1 nm (1Å). However, the X and Y interferometers that measure displacement with respect to the X and Y ultra precision metrology reference mirrors (a form of metrology frame, see section 4.2 above) have been improved to operate at a resolution of 0.05 nm i.e. 0.5Å or about one-fifth the distance of typical inter-atomic spacings.

The target of 0.1 nm accuracy over 50 mm explains the extraordinary care that has had to be taken in the design to isolate it from environmental effects such as seismic vibration (the structure has a first resonant frequency of 2 KHz) and active vibration isolation; acoustic vibration (acoustic isolation shell); temperature changes (temperature control shell); humidity, CO_2 content and temperature (vacuum system, 10^{-7} Pa). Control of temperature is maintained to better than 0.0005°C (0.5 mK).

The machine can be calibrated against an **atomic length standard** e.g. single crystal surfaces with known atomic order and spacing (0.54 nm in silicon). In designing this remarkable machine all of the Eleven Principles and Techniques listed in section 4.2 above were observed and employed.

6. *Ultra-precision machining*

6.1 Energy beam processes

As briefly indicated in section 1.3, '**atomic bit processing**' for both material removal and accretion can be achieved by fine focusing beams of very high energy particles on to the workpiece (Figs. 5, 7).

The industrial applications of energy beam processing have rapidly increased over the last twenty years, driven in particular by the electronics and computer industries. Electron beam (EBM), focused ion beam (FIB) and reactive ion etching (RIE) are effectively swarf-free, virtually zero force processes. They can be used for material removal, accretion and surface transformation, if necessary on a molecular scale. The most widely used energy beam processes are listed in section 1.3.

Electron beam and ion beam techniques are essentially electro-thermal processes which can deliver high density energy to the workpiece in the order of 10^6 Joules/cm^3 needed to remove material in the so called 'atomic-bit' processing mode. Holes of 4 nm have been produced at Cambridge University, where it has been demonstrated that with high speed raster scan electron beam drilling on a very thin substrate of silicon fluoride, it would be possible to write the complete 29 volumes of the Encyclopaedia Britannica onto the head of a pin (Fig. 6). A more typical application of these techniques is the use of focused ion beam machining, (FIB) for the cutting and repairing of individual tracks in integrated circuits (Fig. 8).

One of the brightest sources of finely focused high energy **photons** is the ultra violet light emitted by excimer lasers especially at the wavelengths of 193 nm to 353 nm. These intense 10 to 20 MW energy photons interact directly with the chemical bonds which hold most molecular based materials together causing rapid dissociation and material removal. They allow the cutting of delicate materials, almost without thermal damage. They can therefore be used by surgeons to correct short-sightedness by reshaping the surface of the cornea of the eye. Other applications include micromachining fibre optic clamps, microdrilling helical grooved holes in ink- drop forming nozzles for ink jet printers and minute holes in circuit boards that connect silicon chips in high speed computers. The delicacy of the process can be seen in (Fig. 20), which shows a human hair which has been micromachined, with no discernible thermal damage, by excimer laser mask projection.

Fig. 20 here

Other energy beam processes are listed in section 1.3 above; those of particular importance not described elsewhere in this paper are **chemical vapour deposition** (CVD, plasma and laser enhanced) and **physical vapour deposition** (PVD, sputtering and ion plating). CVD and PVD are both used for producing wear and corrosion resistant coatings. Other uses include the modification of component surfaces and the production of metallic and non-metallic (e.g. ceramics) powders, down to nanometre particles size. Virtually any metal, alloy or compound can be deposited and applications are found in the fields of electronics, semi-conductors, solar energy, optics and decorative coatings. These techniques, also known as **vapour phase epitaxy**, are used to produce semi-conductor super lattices. Thin film deposition systems with deposition rates controlled to better than 0.1 per cent are possible and layers can be deposited as small as one atom thick [2]. These thin film deposition techniques represent the ultimate in micro-structural control.

The energy beam processes are particularly appropriate for microengineering and nanotechnology applications. However the cutting and grinding processes, that have been greatly refined and developed over the last 20 years, will continue to have wide application in ultra precision machining.

6.2 Solid tools

The last 30 years has seen a great development in advanced CNC machines for diamond turning, and the grinding of brittle materials e.g. glasses and ceramics with very low levels of sub surface damage. During this period the number of applications for single point diamond turning has increased significantly for components such as computer magnetic memory disc substrates, high performance aspherical mirrors and lenses, x-ray mirror substrates, etc. Solid tool machining of metals using cutting tools or abrasive grains, for chip thicknesses less than 1 μm (Fig. 21) results in high cutting forces and temperature at the cutting edges [3].

Fig. 21 here

In the cutting depth range of 1nm to 100 nm or so, this is caused by the need to overcome atomic cluster bonding forces. In the range of 0.1 μm up to 10 μm the cutting forces reduce because the machining results in subgrain slipping failure of moveable dislocations for ductile materials, or by subgrain crack fracture of existing microcrack defects in brittle materials. For depths of cut in excess of 10 μm the defects are caused by the more conventional ductile failure in the multigrain range, or brittle fracture at the grain boundaries. It is clear therefore that solid tools are not ideal for atomic bit processing. Most of the newer high performance materials that have been developed over the last 25 years are essentially hard and brittle. However, a new fixed abrasive grinding process using very fine diamond (or CBN) grits has been developed called 'ductile regime' or 'shear mode' grinding. This is starting to replace conventional lapping and polishing to produce mirror surfaces on glasses particularly for higher cost, non-flat, non spherical optical components. However fixed abrasive grinding wheels with very small grits can be inefficient through 'loading' i.e. the grinding surface can become filled or 'clogged' with swarf or chips of the workpiece material. This would require frequent dressing of the wheel; a new abrasive surface would have to be produced by removing the clogged or loaded layer. A new 'Electrolytic In-Process Dressing' (ELID) technique [14] has been developed to overcome this loading problem, (Fig. 22); this can continuously electro-etch the metal bond of the grinding wheel in a highly controlled manner to unclog the wheel and enhance tool life. Ductile mode CNC grinding now appears to be a major contender to produce complex optics in minimum time and at low cost. With the use of advanced CNC machines both transmission and reflecting elements can be generated with very little (or even effectively zero) sub-surface damage or subsequent polishing. This is particularly advantageous for manufacturing complex optics, including off axis optics such as segments for very large telescope mirrors.

Fig. 22 here

In order to achieve ductile mode 'damage free' machining, of brittle materials, extremely small chip thicknesses are necessary, typically in the order of 100 nm [15]. These fine chip thicknesses are necessary to keep the stress in the material small enough so the material yields in a 'ductile manner' rather than by brittle fracture. Fig. 4 illustrates the mechanism of ductile, or shear mode, grinding of a brittle material. This ability to machine brittle materials in a ductile manner is also appropriate for machining complex macro-components in ceramics and bimetallic materials such as turbine blades, nozzle guide vanes, ink jet nozzles, etc. to high accuracy without inducing microcracking which would lower ultimate rupture strength and fatigue life. Clearly the type of machines capable of producing such components with the required mechanical properties, to accuracies in the sub-micron and approaching the nanometre regime, necessitate the development of appropriate ultra precision CNC machine tools. High loop stiffness between the tool and workpiece, for the close control of the tool-to-workpiece position under vibration inducing grinding is essential to achieve 'ductile mode' machining, (see section 4.4 above).

6.3 Ultra-precision machine tools

Examples of ultra-precision machine tools capable of nanometric tolerances on macro components which have been developed in the last 25 years include the Nanocentre (UK) (Fig. 23), the Large Optics Diamond Turning Machine (LODTM) (USA) shown in Fig. 24, and Disk and Wafer Edge Grinding Machines (UK) shown in Fig. 25. The Nanocentre, a 3-axis ultra precision CNC aspheric generator, is thought to be the world's most accurate machine tool of its type. It is designed for very high dynamic loop stiffness between tool and workpiece in both single point diamond cutting and 'ductile mode' grinding. This is achieved through an optimised machine configuration and the use of high stiffness servo drives and hydrostatic bearings throughout. Servo resolution of the X and Z linear axes is 1.24 nm; the rotary 'B' axis for "tool normal" single point turning has a resolution of 0.3 arc sec. An upgraded research machine has produced surface finishes superior to anything reported elsewhere in the single point diamond turning of optical germanium (0.8 nm Ra), Fig. 18 and in the ductile regime grinding of glasses and ceramics [16].

In order to maximise the geometrical accuracy of the Nanocentre, the research machine built under the UK's National Initiative on Nanotechnology (NION), incorporates a 'metrology frame' (Fig 26) to optimise the in-process measurement of the linear motions. This automatically compensates for Abbe offset errors for both pitch and yaw in the XZ plane at the height of the workspindle centre line. This system also measures straightness and orthogonality errors, which are also software compensated. The highly stiff metrology frame structure utilises two ultra precision Zerodur 'stick' mirrors for 3 laser interferometer air paths which are software compensated on line, for refractive index changes, by a differential refractometer. The use of these computer software error compensation techniques broadly described in section 4.3 above, improves the intrinsic horizontal straightness error motion of the XZ motions from 200 nanometres to 50 nanometres (Fig. 27).

The Large Optics Diamond Turning Machine (LODTM) was developed at the Lawrence Livermore National Laboratory, in the USA, to diamond machine large optical components with a surface finish of the order of 2 to 4 nm Ra. Temperature control in a specially environmentally controlled room includes a high velocity air shower controlled to 0.01°F. Refractive index errors, caused by environmental effects such as changes in temperature, pressure and humidity, are minimised by the use of evacuated steel bellows which enclose the interferometer beam paths.

The edge grinding machines, utilise the 'ductile' grinding technique for the finish machining of ceramic and glass disc substrates for the computer magnetic memory disk drive industry; more recently they have been developed for the precision finishing edge grinding of silicon wafers up to 300 mm in diameter.

Figs. 23,24, 25, 26, 27 here

7. Scanning probe microscopy (SPM)

7.1 Background - from optical to electron microscopy

In 1873, Abbe [16] showed that the minimum feature that can be resolved in a conventional optical system is determined by a simple relationship involving the aperture of the system and the wavelength of the light used. For many years it was believed that this was the fundamental limit to the resolution of any microscope and that features smaller than this "Abbe Limit" could never be seen. By this formula, the resolution of a conventional optical microscope is limited to about 1 μm. However many developments in 'microscopes' that have much greater resolving power have been made resulting in instruments with atomic resolution; they can 'see' atoms. They are essentially electronic. The **transmission electron microscope** (TEM), which was invented in 1931 by Ernst Ruska and Max Knoll, uses electrons which have been accelerated to an energy of hundreds of **KeV** when they have an equivalent wavelength of about 0.001 nm (1 pm), and because of this short wavelength, with electromagnetic lenses analogous to those in an optical microscope, resolutions of 0.1 nm i.e. atomic resolution can be achieved. In this type of microscope, the Abbe Limit is not exceeded and the resolution is limited only by aberrations of the electro magnetic lenses.

The principle of making a 'microscope' by scanning a physical probe across the surface of an object and measuring a consequential effect due to its features has been known for many years. Probably the first of these microscopies was the **Scanning Electron Microscope** (SEM). In this an electron beam is focused into a small spot on the object and electromagnetically raster scanned across it. Images can be formed by collecting the secondary electrons generated by the impact of the impinging electron beam, by detecting the backscattered electrons or by detecting the x-rays generated. In this way, several different aspects of the object can be characterised, including morphology, average atomic number and composition and some of these aspects to a resolution of a few nm. Here again, however, the wavelength of the probing radiation is much less than the minimum observable feature size. The resolution is limited by the electron beam spot size which in turn, is limited by the electron source and electromagnetic lens aberrations.

The first suggestion of a form of super-resolution microscope (in which the resolution is less than the probing wavelength) was made by Synge in 1928 [17]. He suggested that it might be possible to fabricate a tiny, sub-wavelength-sized aperture at the end of a glass rod and, by sending light down the rod and scanning the tip raster-fashion across a surface, build-up an image of a surface with a resolution equivalent to the size of the aperture. However, the principle was not demonstrated experimentally until 1972 when Eric Ash from University College in London [18] showed that it was possible to form images of physical features with an electromagnetic probe whose wavelength was many times their size. This was done using 10GHz (30 mm wavelength) electromagnetic radiation in an open resonator formed by a parabolic reflector and a metal plate with a small hole in it. While there is no radiation from the hole, there will be an electromagnetic wave of exponentially-decaying amplitude, called an **"evanescent wave"**, extending beyond the hole. Any object placed within that field will affect the amount of radiation reflected from the plate and hence the impedance of the resonator. If the object is mechanically scanned in front of the hole, the changes in resonator impedance can be used to detect and measure features on the object which are of the same order of magnitude in size as the aperture. They demonstrated that they could resolve a grating with a $\lambda/60$ period (0.5 mm) using a 0.5 mm aperture.

7.2 Scanning tunnelling microscopy

The **Scanning Tunnelling Microscope** (STM) uses a similar principle [19]. Here, the evanescent wave is an electron wave function with an intrinsic wavelength of about 1 nm which extends beyond the surface of a sharp metal tip, as shown in Fig. 9. If a conducting surface is brought to within about 1nm of the tip and a potential difference is applied between them, then a 'tunnelling current' will flow; this was first discovered by Young and Teague at the USA's National Bureau of Standards in the 1960s. The magnitude of this current is an exponentially-decaying function of distance and is also dependent upon the difference between the work-functions of the two materials. Thus, information can be derived about both the topography of the surface and its chemical make-up. The tunnelling current is about 1 nanoamp and decreases by 10% of its value for each 0.1 nm increase in distance The tunnelling current is measured and compared with a reference; the height of the tip (z-direction) is servoed by a piezoelectric device to maintain a constant current. The practical realisation of the microscope also uses a piezoelectric device (see Fig. 9) to scan the tip across the specimen surface in X & Y directions. It is possible in this way to obtain spatial resolutions of about 0.01 nm (10 pm) in 3 dimensions and thus to image individual atoms on a surface. One of the first discoveries using the microscope was the 7 x 7 rearrangement of atoms on the surface of silicon, long-predicted theoretically but never observed directly until the invention of this technique. A wide range of scanning probe 'microscopes' have been developed since Binnig and Rohrer of IBM, Zurich, shared the Nobel Prize for physics in 1986 for achieving atomic resolution with their STM, see Fig. 10.

Several extensions to STM techniques have been demonstrated, including **Scanning Noise Microscopy** [20], in which no bias field is applied to the tip, but the broadband rms noise (which is proportional to the tip-to-sample resistance) is used to control the tip-to-sample distance. This can be used to permit measurements of parameters such as thermoelectric voltage which would not normally be measurable by the STM.

A further modification is the **Scanning Tunnelling Potentiometer** [21]. Here, an ac voltage signal (usually a few KHz) is applied to the tip to generate an ac tunnel current, which is used to control the tip-to-sample spacing. An independent control loop is used to maintain a zero dc tunnel current so that the tip voltage then tracks to surface voltage on the sample. This can be used to measure the nanoscale potential variations in, for example, Schottky barriers or even on insulating substrates.

Other important extensions to the STM principle use the fact that the asymmetry of the junction makes it a rectifying contact. This has led to experiments in which **radio frequency** (RF) [22] and even **optical signals** [23] have been rectified and mixed. Photon emission by tunnelling electrons was first observed in 1988 [24] and it has proved possible to map the bandgap luminescence of semiconductors.

The potential of STM as a surface characterisation tool thus extends far beyond the observation of topography and enables one to gather information about the surface chemistry and electronic structure.

7.3 Scanning force microscopy

The limitation of the STM is that it can only work with conducting surfaces. The Scanning Force Microscope usually referred to as the **Atomic Force Microscope** (AFM), was developed to overcome this limitation [25]. The initial instrument used a diamond stylus on a gold foil cantilever scanned lightly across the surface of the specimen, with the repulsion being detected using a tunnelling tip. This was replaced with an opto electronic sensor [26] and atomic resolution imaging has been demonstrated [27]. An attractive-force sensing technique was developed [28] which uses an ac excitation of the probe tip. The change in cantilever resonance frequency is sensed as the tip approaches the sample surface and is affected by the Van der Waals attraction. This type of microscopy has been used for a very wide range of surface characterisation, including:

- **magnetic force microscopic imaging** of magnetic domains [29] in hard and soft materials e.g. for information storage.
- **electrostatic force microscopy** for studying charge injected into electrets or voltages on semiconductor circuits.

It is fair to say that this type of ac AFM is probably the most-commonly used mode in commercial instruments.

7.4 Other scanning probe microscopies

A wide range of scanning probe techniques has been explored and it is impossible to review them all here. The reader is referred to reference [30] for a more-complete summary. Two of the more useful are **Scanning Thermal Microscopy**, which detects the flow of heat from the tip to the sample using a fine thermocouple as the probe [31] and **Scanning Near Field Optical Microscopy** (SNOM) [32] following the original ideas of Synge [17]. Here, an optical fibre is drawn down to a fine tip. The light reflected from the tip of the fibre as it is scanned is used to reconstruct the surface image. This is useful for obtaining an image at optical frequencies but at sub-wavelength resolution. **Scanning Electrochemical Microscopy** [33] is being used to map electrochemical potentials.

7.5 Non-imaging applications

The huge sensitivity of the scanning probe techniques is now being applied to a wide range of other applications. These include:

- accelerometers using the sensitivity of a tunnelling probe to detect very small movements of a proof mass. In some versions of these, electrostatic attraction is used to servo the mass to a null displacement position [34].
- chemical and calorimetric sensors using the flexure of an AFM cantilever as the sensing element [35, 36]
- manipulation of atoms on a surface by both STM and AFM probes. In the former, atoms on a clean surface have been picked-up, moved and replaced in new positions by applying potential pulses to the probe tip. As indicated in section 2.4, this method was used in 1990 to produce the letters IBM, picked-out by 35 xenon atoms on the surface of a nickel substrate (Fig. 11). Whereas this wok was performed at 4.2K, AFM probes are now being used to manipulate more complex molecules such as porphorins on surfaces at room temperature[37] whose conformations on the surface can be identified and modified[38].

8. Semiconductor devices

8.1 Background

Everyone is familiar with the impact which **semiconductor** technology is having on the sophisticated electronic systems which assist in almost every aspect of modern society, especially health care, medicine and safety. In Feynman's prophetic lecture "There's Plenty of Room at the Bottom" [4] he correctly foresaw the emergence of the integrated circuit with many components on a single piece or "**chip**" of semiconductor and the impact that miniaturisation would have on the capabilities of electronic computers. He also predicted the emergence of the fabrication methods which are now used to make integrated circuits, including electron beam writing. The silicon chip has been doubling its capability every 18 months since its invention in the late 1950s (Moore's Law [39] - see Fig. 28) and has penetrated our every-day lives to the extent that even quite humble domestic appliances such as toasters or irons can have a computing power within them that, 30 years ago, would have been found only in the mainframe computers of large corporations. Huge benefits have accrued from this "silicon revolution", not only economically but also in quality of life for many people. The semiconductor industry is now of enormous world-wide economic importance, with a size of the order of US$100 bn, and which is expected to double by the year 2000.

Fig. 28 here

8.2 Smaller dimensions and photo lithography

Until now, the enormous growth in silicon chip capability has been based on the continuous shrinkage of the dimensions of the individual transistors and the connections between them, which increases the number of components on the chip, increases their speed and reduces their power consumption, while at the same time reducing the time delay for electrical signals travelling between them. The physics upon which the transistors is based, predicts that they will work as-now at dimensions down to (0.03 μm) and thus, the drive to make higher performance chips reduces to the problem of how to make ever-smaller features. The smallest structural dimension in the present (1997) generation of 16 **Mbit** commercial memory chips, traditionally the type of chip that leads the development of the technology is 0.35 μm. These dimensions are printed using a process known as **photolithography**, in which **ultraviolet** (uv) light from a mercury vapour lamp is shone through a mask containing the features of the chip and projected onto the surface of the silicon wafers in a machine known as a photolithographic "stepper" - so-called because it prints an image of one chip and then 'steps' to the next location on the wafer to print the pattern for the next, and so-on. There are two mercury spectral lines in use, at 436 nm and 365 nm, known as the "g" and "i" lines respectively. With a variety of technical innovations, it has proved possible to achieve the 0.35 μm line widths using the i-line, but this is now considered to be the practical limit. Thus further technical solutions to the problem of printing fine lines need to be found if the pace of silicon technology improvement is to be maintained in accordance with Moore's Law. In particular, if the target for introducing 1**Gigabit** (10^9 bits) memory chips is to be met early in the next century, it will be necessary for feature sizes to be between 0.2 μm and 0.1 μm. To go beyond this and to achieve memory sizes of 16 **Gbit** in production, it will be necessary to go below 0.1 μm (100 nm), which is well into the region of nanotechnology [42]. Many companies are currently assessing the use of photolithography using the light from an excimer laser with a wavelength of 193nm as one possibility to achieve feature sizes of about 0.18 μm, but there are severe technical difficulties associated with this; one example is problem of making lenses work at this wavelength. It has been pointed-out that while prototypes have been demonstrated using early steppers working at this wavelength, the task of bringing these to production is lagging about 3 years behind the schedule outlined for 1Gbit chips. It may be that 193 nm photolithography will not prove to be a practical proposition. The two main alternatives are **X-ray** and **electron-beam lithography**.

8.3 X-ray lithography

In X-ray lithography, much shorter wavelength radiation of about 1 nm is used, hence the term **nanolithography** [40]. In principle, this should be the obvious choice for the very fine line widths as it does not suffer from the problems of diffraction associated with the ultra violet (uv) steppers. However, there are many formidable technical problems here. The first is associated with sources of radiation. One possibility is to use the X-radiation emitted by electrons as they circulate in a storage ring, known as a **synchrotron**. Until recently, such facilities have been so expensive that providing them has been the province of national governments. However, the UK manufacturer, Oxford Instruments have made and sold a small number of commercial storage rings. These are still very expensive (US$ 20 m - 50 m each), although each machine will supply radiation to up to 16 stepper stations. Alternatives include the use of high energy laser pulses to vaporise metals, the plasma then emitting 'soft' X-rays. The second problem is associated with the lack of available lenses to focus the X-rays, so that the mask image can be demagnified onto the chip. This means that each mask must have the same dimensions and dimensional tolerance of the chip itself. There is research in progress into the use of multilayer coatings on mirrors to reflect the X-rays, but the mirrors themselves need to be shaped and smoothed to 0.1 nm precision over an area of many square millimetres, a severe challenge for the machining aspects of nanotechnology outlined in section 6 above. Finally, the masks themselves need to made from a combination of materials which are either transparent or opaque to X-rays. Achieving the required opacity in the lines is very difficult. Gold and tungsten are the preferred materials, but they need to be laid down in layers up to 0.5 μm thick on a thin silicon membrane. If the required feature is only 100 nm wide then there is a real problem with the height to width aspect ratios of the features on the mask.

8.4 Electron beam lithography

An alternative process which certainly permits the fabrication of lines less than 100 nm wide is electron beam lithography. This uses a machine similar to a scanning electron microscope (Fig. 5) to "write" a pattern into a plastic resist with a finely-focused electron beam. The fundamental problem with this process is that it is inherently slow, because each line on every chip on a wafer must be written sequentially. Hence, the process has only been used commercially for very small runs of special or prototype devices or for semiconductor devices on which there are very few lines which need to be so narrow. An example of the latter is the high electron mobility transistors fabricated on gallium arsenide for microwave applications, where there are very few lines on a chip and most of the device can be made using conventional photolithographic processing.

A further application of the electron beam (EBM) process is the production of masks for optical and X-ray lithography. A related process, focused ion beam (FIB) lithography, in which the electrons are replaced by high energy ions (Fig. 7), may hold some advantages in resolution in that the secondary electrons produced in the resist by ion bombardment are of very low energy in comparison with those produced in electron bombardment. Research is in progress on the use of improved projection systems for both EBM and FIB techniques to overcome the problem of very slow serial scan and thus low productivity [41].

8.5 SPM possibilities

Finally, the invention of the scanning probe microscope as described in section 7, has led to a number of researchers exploring the possibility of using a scanned tip to "write" patterns on a silicon chip at the nanometre level. It has been shown to be possible to use electron emission from an STM tip to write patterns in a polymer resist, which can subsequently be replicated in metal. Gold lines as narrow as 20nm have been produced in this way [43]. In order to make such patterning techniques viable, it will be necessary to produce arrays of large numbers of tips, each of which can be individually steered. Such arrays have been made for vacuum microelectronic display applications and it has been demonstrated that piezoelectric layers deposited on cantilevers can be used to steer STM tips over quite large areas [44]. Basic feasibility of the generation of lines has thus been demonstrated but a great deal of research needs to be done before a process could even be used to make chips in research, let alone production.

8.6 An uncertain way forward?

It can be seen from the above that there are formidable technical obstacles to the fabrication of chips on a commercial basis with line widths down to 100nm and less. Even for a 200 nm line width

Tolerance on linewidth is	20 nm
Killer defect size is	40 nm
Mask registration tolerance is	50 nm
Mask accuracy (feature to feature) is	10 nm
and on the normal 10 : 1 manufacturing to metrology rule, then,	
Metrological accuracy needed is	1 nm

This represents an enormous challenge in large scale manufacture. The required metrological accuracy shows the need for fundamental nano-metrology equipment such as the NIST 'Molecular Measuring Machine' described in section 5.4 above.

Furthermore is not clear which of the lithographic routes of those outlined above, if any, will be successful on a commercial scale. It has been pointed out that we may be approaching a fundamental technological limit to the continuing development of the semiconductor industry in the direction of ever-increasing performance based on higher packing densities and smaller linewidths and that the future in the next century may lie in greater diversification of the functions that can be achieved on a single chip. Certainly, the costs of the present generation of silicon fabrication plants is prohibitively expensive for all but the largest companies or even countries, with US$1 bn to US$ 2 bn becoming the norm. It is clear, nevertheless, that the market rewards of continuing to push the barriers forward are also very large, with a world market of US$100 bn, doubling every few years. Therefore there is a very powerful impetus to maintain the present technical improvement rate. If this is to be done, the full armoury of nanotechnology techniques and processes outlined in this article will need to be applied to solving the technological problems.

For further reading on this topic, please see references [40 to 43].

9. *Microsystems Technologies (MST) and Micro-electro-mechanical Systems (MEMS)*

9.1 Background

The power and the capabilities of silicon integrated circuits was expounded in section 8, but it is fair to say, however, that powerful as these chips are, they are only useful if given information which they can process and then act upon. This is frequently achieved via a range of external sensors. In many cases they will communicate the results of their computations either with other chips or ourselves through a variety of links such as wires, optical fibres, visual display units etc. They may also demand the generation of some mechanical function via an actuator such as a motor or a pump. These peripheral functions are currently provided as separate components which must be individually manufactured and then assembled into a complete system; this can be a costly process which also greatly increases the size of the finished system.

Microsystems engineering [45] aims to exploit the increasing signal processing power which can be integrated on a single silicon chip by putting it together with the sensing, actuation and communications functions into a single microassembled or integrated package, as shown in Fig.29.

Fig. 29

The sensor and actuators can either be assembled with separate silicon chips into a package to make the microsystem using hybridisation methods (e.g. chip-and-wire or flip-chip bonding) or these functions can be made on the same chip of silicon as the processing circuits. There are clear advantages of cost, system size and achievable manufacturing volume in doing this. Either way, there is a requirement to make very small mechanical components which can move and/or to integrate materials for sensing or actuation functions which are not traditionally part of the integrated circuit (IC) engineer's repertoire. This is called **microsystems technology** (MST) or in the USA, **micro-electromechanical systems (MEMS)**; it presents new challenges in terms of process integration and device design which go well beyond the normal requirements of IC manufacture. There can be, for example, a need to design and make freely-suspended or moving 3-dimensional structures in which the individual components may be only 1 μm - 2 μm thick. These may incorporate materials which would not be compatible with a normal silicon processing environment; the challenges posed by this are addressed below.

Examples of microsystems which are already bringing real benefits to society include:

- Accelerometers and gyroscopes for automotive applications, particularly for air-bag sensors, automatic suspension and navigation systems
- Uncooled passive infra-red (PIR) sensor arrays which image the infra-red radiation (IR) emitted by people are now used in applications such as firefighting and retrieving survivors from collapsed buildings.
- "Smart" pills and catheters incorporating pressure, temperature, chemical and acoustic sensors for diagnostic use.
- The concept of the "laboratory-on-a chip" incorporating means for synthesising, pumping, handling and testing chemicals is one that is gaining great interest in the pharmaceutical field.

9.2 Microsystems and nanotechnology

The critical dimensions in many microsystems are of the order of 1 μm and thus are not strictly in the nanotechnology range. However, many authors consider the topic to fall into the general area of nanotechnology and there is, indeed, a significant area of overlap between the fields. In particular, there are contributions which MST and MEMS can make to nanotechnology. For example, there is considerable promise in integrating the components of a highly miniaturised scanning probe microscope (sensors, actuators, amplifiers etc) onto a single chip and significant progress has been made in this direction [46]. The likely benefits of this work will be the reduction of the cost of these tools to the extent where they may be used in, for example, individual molecular sensors.

Several processes used in microsystem fabrication have nanometric accuracy capability.

9.3 Processing technologies for microsystems

The vast majority of processing technologies which have been applied to the fabrication of microsystems have evolved from those developed originally for IC manufacture and packaging. Hence, all the traditional processes of thin film metallisation and photolithography are used. The need to fashion 3-dimensional structures is being met in a number of ways, which have been reviewed in [45] but are summarised as follows:

- **bulk micromachining** based on chemical etching processes; it has been known for many years that single crystal silicon can be etched using a variety of chemicals, for example potassium hydroxide/propanol or ethylene diamine/pyrocetechol solutions [47]. These etchants tend to attack certain facets of the cubic silicon structure much more rapidly than others. For example, an etch rate ratio of 50:1 can be achieved between the (100) and (111) direction crystal facets. The etch rates can also be controlled by doping the silicon, so that a heavily p-doped region will act as an effective etch stop or by electrically-biasing a p/n junction. Thermally or chemically deposited glass layers, which can also be patterned by photolithography and etching, can be used as etch masks or as mechanical components in their own rights. Polysilicon layers, which can also be chemically doped to provide etch selectivity, can also be used as mechanical components. This crystallographic and chemical selectivity can be used to create quite complex structures in the silicon such as cavities, membranes and suspended masses, which can be used for devices such as pressure sensors and accelerometers.

- **surface micromachining** - a process related to bulk micromachining but instead of etching structures into the bulk of the silicon, it seeks to grow all the components on the surface of the wafer. Examples of the materials used include phospho-silicate glasses for the sacrificial layers and polysilicon [48] or silicon nitride for the mechanical components. The advantage of this type of process relative to the bulk micromachining is that the silicon itself remains undamaged so that it can all be used for electronic signal processing components.
- **LIGA** - (from the German: Lithographie Galvanformung und Abformung) is a deep etching process based on lithography, electroplating and moulding [49, 50] The LIGA process in its original form uses X-rays from a synchrotron to expose a thick layer of photoresist, to a depth of up to 1000 μm (1 mm) but with a lateral resolution of better than 1 μm. Thus, very high vertical aspect ratio components can be formed in the resist. These are generally replicated by an electro-plating process to make a master, which can then be used to mass-produce the original object by embossing or injection moulding, in a fashion related to the process that was used for making vinyl gramophone records. A variety of process have been devised which are related to this but which do not use the high-cost radiation from a synchrotron to create the prototype shape; they use either conventional photolithography to pattern a thick photoresist or use an ultra-violet laser such as an excimer laser to etch a pattern directly into a plastic to act as a micro mould.

9.4 Sensing and actuation materials for microsystems

The range of sensing materials which will turn a stimulus from a measurand into an electrical or an optical signal and which have been, or are being, applied to microsystems is shown in Table 1. The corresponding measurands are also shown in this table. The practicality of many of these systems has been established, although not all have yet been commercialised.

Sensing materials

- Oxides and other inorganic compounds
- Semiconductors
- Metals
- Polymers
- Organics
- Biochemicals
- Biologicals

Measurands

- Light or infra red (IR)
- Magnetic/Electrical Fields
- Sound
- Pressure
- Acceleration/Rotation
- Pollutants
- Antibodies/Toxins
- etc

Table 1 Sensing materials and measurands for microsystems applications

In the case of actuation the range of techniques, and the corresponding materials, for turning an electrical signal into a physical motion is much more restricted. The prospective candidate materials are listed in Table 2 and their characteristics in Table 3 [51].

Actuation Techniques

- Piezoelectric
- Electrostatic
- Electromagnetic
- Electrostrictive
- Magnetostrictive
- Ionic flow (cf muscle)
- Martensitic transitions (thermally or electrically driven)

Materials

- Ferroelectric oxides
- Polymers
- Magnetic materials
- Biological materials
- "Memory" metals/ceramics

Table 2 Actuation techniques and possible materials for use in microsystems

Class	Stress NM/m^2	Stiffness GN/m^2	Strain %	Strain Rate s^{-1}	Power W/kg	Energy kJ/m^3	Efficiency %
Piezo-electric	35	40	0.09	>10	>1000	> 10	> 30
SMA	> 200	78	> 5	3	> 1000	> 10	> 3
Electro-static	0.04	< 0.01	> 10	> 1	> 10	1	>20

Table 3 A comparison of piezoelectric, SMA and electrostatic actuation for microsystems applications

The most promising of these for microsystem applications are the **Shape Memory Alloy** (SMA) materials [52] which are characterised by moderate displacements and high forces but with low thermal efficiencies, **electrostatic actuators** (which are characterised by high displacements and good efficiencies but with low forces) and **piezoelectric/electrostrictive materials** (which are characterised by low displacements and high forces with good efficiencies).

Of all the new materials being assessed for microsystems, the **ferroelectric** materials are the most interesting because they allow the designer to combine a variety of useful properties by virtue of their polar crystal structures. These useful properties of ferroelectrics are:

- **piezoelectric** - which means that they will generate electrical signals when stressed and can be used in sound, pressure and acceleration sensors. A piezoelectric material will also undergo mechanical strain when an electric field is applied to it and thus can be used for actuation in pumps, vibration control components, motors etc. In its most accurate servo control application it is used with picometre precision in scanning probe microscopes. This effect can also be used for generating electro-mechanical resonances which can be used for frequency control and filtering as well as chemical and biochemical sensors. Ferroelectrics such as **lead zirconate titanate (PZT)** exhibit some of the strongest piezoelectric effects known.
- **pyroelectric** - by which effect, electrical charges are produced when the temperature of the material is changed. Extremely small changes in temperature (less than one tenth of one millionth of a degree Celsius, <1 x 10^{-7}°C) can be detected and, with the appropriate thermal structure and electrical amplification, they can be used as very sensitive detectors of infra-red radiation. Arrays of such detectors can be used to create thermal images from heat (infra red) radiation. Unlike more conventional detectors of such radiation, they need no cooling and are thus low power and easy to use. Again, compositions related to PZT are particularly interesting in this area.
- **electro-optic** - an effect which can be used to modulate light signals passing through the ferroelectric material and hence to communicate information. Lanthanum-doped PZT compositions show some of the strongest electro-optic effects known.

Ferroelectrics also show high dielectric constants and dielectric hysteresis which can be used in electrical capacitors and non-volatile memories in microsystems.

Over the last 10 years, a range of processes have been used to grow films of materials such as PZT onto silicon and other substrates. These have included deposition from solution, from the vapour phase and by evaporation or sputtering in a vacuum. The critical issue for applications to microsystems will be how best to obtain good quality thin films (1 μm to 5 μm thick) on silicon devices at a processing temperature of less than 500°C [53].

9.5 Applications of microsystems

Microsystems, incorporating sensing, actuation, signal processing and communications functions incorporated in a micro-assembled package or integrated into a single chip, are rapidly emerging as devices which are likely to be of major economic importance in the future [54]. This has been recognised in several European countries and the topic has received a substantial boost in the Framework 4 research programme in the European Community [54]. Currently-available commercial microsystems incorporate only sensing, signal processing and communications functions.

- **automotive applications** - examples include sensors for various automotive functions [55], such as manifold air pressure (MAP) sensors which are used, together with exhaust oxygen content sensors in closed-loop control of engine fuel systems. The MAP sensors use a micromachined diaphragm of silicon which is exposed to the inlet manifold pressure. The displacement of the diaphragm is either measured using piezoresistive sensors implanted in it or from the change in capacitance relative to a capacitor plate placed adjacent to it. In the last two decades these sensors have helped to raise the average fuel consumption of US cars from 4 to 12 km per litre. The accelerometers which are used for controlling air-bag inflation command a large and growing market. These use a proof mass of silicon suspended on a silicon membrane and the displacement of the diaphragm is again sensed either capacitatively or piezoresistively. Other automotive applications include sensors for 'smart' suspension systems, anti-skid braking etc.
- **medical applications** - in the field of medicine, similar technologies have also brought great benefits. The MAP technology inspired manufacturers to develop a disposable blood pressure transducer (DPT), leading to a drop in unit price relative to the previous technology, from US$600 to US$ 10. Other applications include intra-uterine pressure (IUP) sensors, angioplasty pressure sensors, sphygmomanometers and many others.
- **consumer applications** - in the consumer market, applications for smart pressure sensors range from scuba diving computers through altitude sensors to vacuum cleaners. One very exciting and potentially large market is for digital projection TV displays. In this case, actuation is fully incorporated. Texas Instruments [56] have developed a Digital Micromirror Device, which produces a modulated image by tilting thousands of tiny mirrors integrated onto chips. The device produces much better resolution and contrast than conventional projection displays for digital imaging especially on large displays.

In all these examples the properties of silicon are used to provide both the sensing and the actuation mechanism in the case of the digital micromirror device. The use of silicon restricts the range of properties which could otherwise be obtained. If, however, novel materials can be integrated onto silicon, then the field of pyroelectric infra-red detection and thermal imaging, for example, could be greatly expanded [57]. Arrays of more than 10,000 IR detectors made by hybridising ceramic detectors onto silicon readout chips, can give thermal resolutions of better than 0.1°C and excellent thermal images [57]. One of the prime objectives for technical assistance to firefighters is seeing through smoke thus overcoming the fire-fighter's greatest hazard: long-wavelength IR thermal imaging achieves this as well as showing where the seat of the fire is. Other IR microsystem applications include thermographic surveys of buildings, machines etc. by industrial users [58], doctors using medical thermography [59, 60] and IR vision enhancement for cars [61, 62]. It has been pointed out that IR vision enhancement can make a major contribution to driving safety [62], and not only on the road. Equipping boats navigating crowded waterways at night with thermal imagers could lead to a marked improvement in safety there as well [63].

- **actuators on a chip** - it is possible to provide some actuation by using electrostatic attraction between two movable components on a chip. These can be made by etching the silicon in a carefully controlled way into complex 3-dimensional structures. Micromotors approximately 100 µm in diameter have been made experimentally in this way [64]. However, the forces which can be generated by electrostatics are very small and very few useful devices have been made using this principle. If actuation with useful force and displacement could be introduced by, for example incorporating a piezoelectric layer on the silicon, then a much wider range of applications and markets would be generated, including micropumps for medical applications and environmental air and water analysis etc. [65], novel fuel injection systems, ink jet printers, motors [66] and microrobotics [67].

9.6 Markets for microsystems

The market for smart silicon sensing devices has grown enormously since 1983, at a compounded growth rate of 22% pa to about US $500m in 1994, much faster than the 3-5% rate of the US$5 bn sensor market as a whole; by 1996 it was estimated to be well into the billion dollar range [68]. The market is now estimated to grow to US$14 bn pa by the year 2000, with the automotive applications - mainly pressure and inertial sensors - accounting for 41% of the total.

The market for uncooled thermal imaging systems is expected to grow markedly [69], to a multi billion US$ pa business by 2005, although this entirley depends upon the reduction in unit price of detector arrays; this can only be achieved by a move to a fully integrated structure using ferroelectric thin films as the sensor elements. An example of one application is given in Fig. 30 which shows a thermal imaging system made by Cairns & Brother in the USA for fire-fighting applications using a solid-state pyroelectric array manufactured by GEC Marconi (UK). Being fully solid state, these are small enough to be helmet mounted and enable fire-fighters to see through smoke without having their hands encumbered by bulky thermal imaging equipment.

Fig. 30

10. Nanostructured materials

10.1 Introduction

The topic of "**Nanostructured (or Nanophase) Materials**" can be defined as the fabrication of materials in which there is some aspect of dimension (for example grain size or layer thickness) which is in the nanometre range. It has enabled scientists to access new ranges of electronic, mechanical or optical properties. Over 2000 years ago, the Romans discovered that the inclusion of very small amounts (approximately one part in 50,000) of gold in glass in the form of either metal or metal salts produced a deep red colour if the glass was appropriately heat treated. On dissolution, and cooling to room temperature, the gold produces a straw colour in the glass, but after annealing the colour "strikes" and a deep ruby-red is formed [71, 72]. Similar effects can be produced by using or copper or selenium. The phenomenon is due to the formation of nano-sized particles of metal crystals in the glass, which form during the annealing process. These are far too small to scatter visible light so the glass retains its transparency. Instead they strongly absorb light of below a certain wavelength, giving the colour observed. Clearly, the physics of this phenomenon would not have been understood by the early glass makers, but it is just one example of how the deliberate nanophase structuring of materials can open-up new options for materials and product design. The following sections summarise the different ways in which such materials can benefit society.

10.2 Optical materials

In the example of the formation of coloured glasses, it is **quantum-confinement** of electrons in the small particles of the conductor that shifts the cut-off edge for the absorption spectrum in the metal into the blue region of the spectrum, which gives the red colour to the glass. Typically, the smaller the crystallite, the wider the gap between the valence and the conduction bands and the shorter the wavelength of the absorption edge. Hence, it is possible to produce powders of a single material, and the semiconductor cadmium selenide is a particular example which has been extensively studied, in which the particle size determines the absorption cut-off wavelength and hence the material's colour. In this material, crystallites of approximately 1.5nm in size will appear yellow, while 4nm particles will appear red. Still larger particles appear black. This principle is now being applied to tailoring the sizes of particles of zinc oxide and titania for sun-screen cosmetics where it is desirable to shield the skin from particularly damaging wavelengths of the ultra-violet component of sunlight. A further promising application of this quantum confinement principle is in the development of semiconductor lasers for the fibre-optic communications market, where it is highly desirable to be able to tune the wavelength of emission, so that many channels of optical information can be sent simultaneously down a single optical fibre. In this case the technology consists of making very small "**quantum-wires**" or "**quantum-dots**", usually in a stack of nanometre-thick layers of different compositions of gallium arsenide in solid solution with aluminium or indium arsenide or selenide. The different compositions enable the technologists to alter the band-gaps of the semiconductor layers, leading to one dimension of quantum electron confinement in a single layer. The physical restriction of the other dimensions of the layers by photolithographic pattern definition and plasma etching is used to create wires or dots. Other layers of materials with different refractive indices can be used to confine the light into the regions of the semiconductor material containing the quantum dot. The technological problems of fabricating these structures and making electrical contact to them are considerable. The fabrication of two and three dimensional arrays of such quantum dots, effectively making a structure with its own set of allowed and excluded optical and electronic states and therefore band structure, also offers new possibilities for active and passive devices. Lasers using quantum well structures based on layers (i.e. with one dimension of electron confinement) are now commercially available and are used in high data-rate fibre-optic communications systems, but the technology for making optoelectronic devices based on quantum wires or quantum dots is still in its infancy and it will be some time before they appear on the market.

10.3 Structural Materials

While the mechanical properties of materials (e.g. yield stress) are ultimately determined by the strength of the bonds holding their constituent atoms together, the actual parameters that are measured for a bulk material are strongly related to their physical form, and particularly the presence of defects. Thus, a thin glass fibre with a defect-free surface can sustain spectacularly high levels of strain without failure while a piece of plate window glass will sustain hardly any strain before breaking, due to the presence of microcracks in the surface. Similarly the hardness and ductility of a metal is largely determined by the ease with which dislocations can propagate through the crystallites which make up its structure. Richard Siegel and co-workers at Renselaer Polytechnic Institute (USA) have demonstrated that the hardness of pure copper is increased by a factor of up to five times when the grain size is reduced to 6nm. This is because the small crystallites cannot sustain dislocations and thus are relatively difficult to deform. An important potential application of this principle is in the design of coatings for advanced damage tolerant surfaces. At Cranfield University (UK), layered microstructures with individual layer thicknesses of between 10 and 1000 nm have been used to produce erosion protection systems for applications as diverse as gas turbine compressor blades and magneto-optical storage disks. In the former case, a 50 μm coating is produced which consists of a stack of metal/ceramic layers with individual layer thicknesses of between 100 and 1000 nm. In the latter case, a ceramic/ceramic multilayer coating is produced which consists of 2000 layers, each 15nm thick. In both cases, the protection is obtained by tailoring the sub-layer thicknesses to the footprint which is generated by the Hertzian contact between an impacting particle and the surface. Thus, larger impacting particles require more-widely spaced layers than smaller ones. Fig. 31 shows a cross section through a 50μm multilayer coating after having been impacted by a 600μm particle travelling at 250ms^{-1}. The coating has not fractured and all of the energy has been dissipated in the elastic rebound of the particle, fracture of the particle or plastic deformation of the substrate. In service exemplified by these conditions, this type of layer can provide a 300-fold improvement in component life when compared with uncoated metal.

Fig. 31

10.4 Self-Assembling Materials

Nature has provided many ways of organising materials into ordered structure, with a reduction in the net free energy being the driving force. An example is the growth of a crystal in which the atoms exhibit long range spatial order from the liquid phase in which they only exhibit short range order. There are many other examples of such thermodynamically-driven ordering, which are starting to be exploited technologically, in which structures are ordered on the nano-scale.

10.4.1 Langmuir-Blodgett (LB) Films

Certain long-chain organic molecules which have a group on one end which is water-loving (hydrophilic) and a water-hating (hydrophobic) tail will organise themselves if floated on the surface of water so that the tail is oriented perpendicular to the surface. (See fig. 32) Such layers can be compressed to form a molecular monolayer which shows long-range crystalline order in the layer plane. Such a layer will be transferred to a flat surface dipped into the water and successive layers can be deposited to build-up structures monolayer-by-monolayer. The technology for this is well advanced, to the point where different materials can be deposited in successive monolayers and their orientation can be controlled. A wide variety of molecules have been configured into such layers, exhibiting a plethora of effects such as optical non-linearity, piezoelectricity and semiconducting behaviour. Potential applications include optoelectronic devices, resists for nanolithography and active layers for gas sensors. (See reference [72] for further information.)

10.4.2 Liposomes

Long-chain molecules, such as phospholipids, which possess hydrophilic heads and hydrophobic tails can also show interesting effects if dispersed in water. They tend to form double or bi-layer membranes with their heads on the outside and the tails on the inside (see Fig. 32-). These membranes will wrap around to enclose tiny spherical volumes, which can be in the nano-size range. These tiny capsules can be made to enclose a wide variety of materials ranging from drug molecules to the cadmium sulphide clusters referred to in section 10.2. The technology promises to be an important underpinning-tool for the manufacture of nano-sized powders. Further discussion of this topic follows in section 11.1

10.4.4 Buckminsterfullerenes

The discovery by Harold Kroto of Sussex University (UK) and his co-workers of the so-called "third-form" of carbon in which the atoms are arranged in spheroidal molecules, and of which C_{60} is the prime example, has led to the development of a whole new range of physics and chemistry based upon these "fullerenes" [78]. Recently, there has been much interest in manipulating these molecules on surfaces using STM methods. One of the interesting developments for the field of nanotechnology is the discovery that these compounds can also form long cylindrical tubes with nano-sized diameters. These can form the smallest electrically conducting "wires" ever made and could be a component in future novel nanoelectronic circuits.

10.5 Further Information

For further information on the topic of nanophase materials, the reader is referred to the references numbered from [72] to [80].

11. Molecular, biological and medical aspects of nanotechnology

11.1 Self-assembly - thin films, liposome-based systems

Previous sections have focused on an extension of traditional approaches to nanotechnology which exemplifies the "top-down" approach to nanotechnology. The alternative **"bottom-up"** approach relies upon exploitation of the fields of chemistry and biology and comprises the formation of structures, both microscopic and macroscopic, from molecular building blocks. The advantages of this approach centres around the ability to produce complex **nano-structured materials** and entities via the relatively simple macroscopic handling of liquids and solids. The challenge becomes the design and synthesis of the molecular building blocks and the understanding of their interactions with liquids, solids and other molecular building blocks.

Biology is a highly complex and feature-rich example of the "bottom-up" approach and is discussed further in sections 11.3 and 11.4. Biology fundamentally relies upon the **self-assembly** of molecular components at nanometre scales and modern chemistry has now appreciated this approach and is applying such concepts in a number of areas. Molecular self-assembly can be summarised as the spontaneous association of molecules into stable, structurally well-defined aggregates or surface-coatings joined commonly by non-covalent bonds. A wide variety of non-covalent interactions are possible including ionic, hydrophobic, hydrogen bonds and van der Waals interactions. The formation of vesicles from a solution of amphiphilic molecules (Fig. 32) is a classic example that has been studied for over a century; Langmuir-Blodgett films is further example. The self-assembly of bifunctional molecules onto solid surfaces (Fig. 32) are examples that have developed recently. All the preceding approaches rely upon a knowledge of how, at molecular dimensions, molecules, solvents and interfaces interact and also on the subsequent design and synthesis of appropriate molecules to exploit this and to result in the desired final nanostructured materials that fulfil the needs of specific applications.

Fig. 32 here

The potential applications of self-assembled approaches to commerce is broad and includes applications within the electronics, medical, analytical and materials industries.

Langmuir-Blodgett (LB) films are typically formed by spreading a molecularly thin layer of molecules at a liquid-gas interface and where molecules of appropriate design, orientate due to preferential interactions with either, or both, the liquid or/and gas. The passing of a surface through the interface, if appropriate conditions exist, results in the transfer of a layer of single molecule thickness, to the surface. Repeated passage can result in the addition of further layers. Although this technique has been known for many decades, only recently have applications with commercial potential been developed. The design and synthesis of molecules that enable defined structuring during the LB deposition technique and that introduce application specific functions to the films are the challenges in this area. Application areas include, sensors, electronics, optics, optoelectronics, formation of resist materials for lithography and use in biological and medical areas [72].

While the LB technique is very broad in the range of films and surfaces that can be utilised, the spontaneous formation of thin film coatings on surfaces directly from solution is appealing. A range of systems have been investigated over the past decade and have become generally known of as **self-assembled monolayers (SAMs)**. These consist typical of bifunctional molecules with one functionality designed to interact specifically with, and bind to, a particular surface, *e.g.* thiols with gold and silanes with oxide surfaces, resulting in the formation of monolayer coatings (Fig. 32). The remaining functionality is chosen to impart desired properties upon the resultant monolayer coating, and hence surface [79]. Applications are being developed in areas similar to LB-films, *i.e.* sensors, electronics, optics, optoelectronics, lithography resist materials and biomedical.

Liposome-based systems are important in the context of self-assembly and 'delivery' of material to a target site. Liposomes are vesicles typically comprised of a small number of spherical lipid bilayer shells enclosing a volume of unstructured material. Liposome size can be varied ranging upwards from diameters of less than 100 nanometres and with size dependent on the materials used and method of production [80]. The material enclosed within liposomes can be varied widely and for many applications the lipid shells of the liposomes serve to protect the contents. Liposomes are thus commonly used to protect and deliver material to a site of interest with applications or potential applications existing within the pharmaceutical industry for drug and gene delivery (see section 11.5), the food industry, *e.g.* liposomes containing flavour oils, agrochemical industry and for cosmetic applications; the latter example being a significant commercial application.

11.2 Supramolecular chemistry

Supramolecular chemistry, another recently established example of self-assembly depends upon the specific recognition and interaction of complementary molecules to direct the formation of structured materials and assemblies. Supramolecular chemistry offers a potentially broader range of applications as the self-assembly of three-dimensional structures is possible and is not reliant upon surfaces and interfaces to direct assembly. Although the breadth of supramolecular chemistry is great, a limited number of demonstrations that fall within the accepted concept of nanotechnology, have been reported. As an example, a series of interlocking and intertwined molecular structures have been formed exploiting the molecular recognition between p-electron rich and p-electron deficient molecular units. The novel molecular architectures formed have been shown to have switchable properties on the nanometre scale suggesting the future possibility of molecular-based electronic circuitry [81].

An area of supramolecular chemistry with more immediate application is that of dendritic polymers. Dendrimers are specific types of molecules grown by repetitive reactions such that each reaction step adds a small and defined number of molecular fragments to a growing molecular framework. The most common example is in the production of nanometre-sized spherical particles with each reaction step adding an additional "shell" to the particle. Particles with highly defined sizes and substructures can be achieved, i.e. size is determined by the number of reactions steps and hence number of "shells", and structure by varying the individual reaction steps. Applications based on these structure-controlled architectures can be found in many areas including life and materials science [82] and with their use in microscopy for size calibration at nanoscales an immediate application.

- Molecular-based manufacture: the Drexler approach

A possible high profile application of supramolecular chemistry and self-assembled systems is the Drexler concept of nanotechnology that relies upon the use of molecular assemblers to select and structure molecular building blocks together [83] (also see section 2.4). Although basic concepts within this area are being investigated, a commercial impact of this approach is unlikely to occur in the foreseeable future due to both technological [84] and economic [85] considerations. Drexlerian concepts are further discussed in the next section (section 11.4) within a biological context.

11.3 Molecular nanotechnology

- Biology as a molecular nanotechnology

Biology is often used both as an example and proof that molecular-based or "bottom-up" nanotechnologies are possible, including those proposed by Drexler and his supporters [84]. Biological examples can easily be found that demonstrate molecular-based information storage, information processing, molecular replication and nanoscale "mechanical" motors. The "pre-programmed" sequences of amino acids and nucleotides in protein and nucleic acid molecules represent routine information storage at a density far greater than currently achievable by modern technologies; *i.e.* approximately 6 x 10^{18} bytes.cm^{-3} [86]. The **transcription** of a single DNA sequence into multiple **RNA** molecules and their subsequent **translation** into protein molecules represents molecular processing of information and molecular replication. **Chemo-mechanical molecules** such as kinesin, a **motor protein**, that directionally transports cell contents along the **internal skeleton structure** of cells, represent single molecule chemo-mechanical motors able to individually generate forces of 5 pN [87]. Further examples can be found in animal muscle - the actin-myosin system - and in the bacterial flagellar [88] (Fig. 33).

Fig. 33 here

Whilst these obvious biological examples have been "designed" by millions of years of evolution to fulfil particular roles, it is hoped that a rational-design approach based-upon our developing understanding of biology and chemistry can improve upon nature and overcome the limitations of natural biological systems such as *(i)* poor performance at elevated temperatures, *(ii)* poor structural performance (for some applications) and *(iii)* a limited range of naturally occurring starting materials.

However, the reality is that while the evocative long-term goals of molecular nanotechnology are well publicised, doubts exist as to the real possibilities of Drexlerian approaches, *i.e.* nanomachines as scaled versions of macroscopic systems. They include arguments concerning thermodynamics and information processing Jones [95]. The goal of molecular-based manufacture of common-place macroscopic items, such as domestic vacuum-cleaners, is, as yet, a distant dream! The immediate applications of molecular-based and traditional nanotechnologies relating to biology are found most commonly within the biomedical, pharmaceutical and analytical sectors. In addition, realistic long-term possibilities have been highlighted by a number of novel demonstrations and which include the demonstration of techniques for the observation and characterisation of individual molecules.

- Single molecule observation

Of the fundamental components required for Drexler-type nanotechnology, the ability to communicate information from the macroworld to the nanoworld and *vice versa* is crucial. This is required both for eventual use in nanotechnology applications and immediately, for characterisation and observation during the development of nanotechnologies. Thus methods for single molecule detection, observation and manipulation is an important area of current investigation. Typical examples include scanning probe microscopy (see section 7) where techniques such as atomic force microscopy (AFM) can image individual biomolecules [89] (Fig. 34), the use of modified AFM probes to measure the force interaction between individual biomolecule pairs [90], observation of the movement of single motor proteins [91], optical detection of single molecules [92] and the controlled manipulation of single macromolecules such as a particulate-labelled DNA molecule via optical tweezers [93] (Fig. 35).

Figs. 34 and 35 here

11.4 Medical and pharmaceutical applications

The possibilities of nanotechnology within medicine is almost endless with futuristic suggestions including injectable nanomachines that would eliminate the requirement for invasive surgery. The immediate reality is less radical.

- Biocompatible textured surfaces

The effect of morphology and topography of surfaces upon cell-surface interactions is now appreciated and the deliberate nano- and micro-texturing of surfaces to produce biocompatible textured surfaces to optimise interactions is being pursued. Applications listed by Meyer and Biehl in 1995 [94] of biocompatible micro-textured surfaces include cell culture substrates, neural implants, prostheses, microsubstrates for bioartificial organs and the regeneration of biomaterials such as bone, tendon and nerves. Specific examples include *(i)* an observed increase in biosynthetic activity and mobility of bone cells on polymer films cast in micromachined moulds, *i.e.* a textured surface, when compared to a smooth control surface [95], *(ii)* the observation of *in vitro* regeneration of severed rat tendons only on textured surfaces and which suggests the possibility of *in vivo* use of textured "bandages" to accelerate healing [96] and *(iii)* the directed growth of nerve cells on micromachined structures [97] with suggestions of eventual artificial neural implants [98].

- Drug delivery: nanoparticles

The use of nanoparticles to direct drug delivery to treatment sites within patients is currently the most active application of nanotechnology to medicine. Nanoparticles have been shown to accumulate at various sites depending on the size and chemical nature of the nanoparticles and mode of administration, *e.g.* intravenous injection can result in accumulation in the liver, spleen and bone marrow. The incorporation of drugs into the particles therefore directs the drugs to the nanoparticle accumulation sites where the incorporated drugs are released, *e.g.* if comprised of biodegradable polymers, the polymer typically degrades at a predetermined rate releasing the drug. Many examples can be found [99] with fabrication being commonly achieved by *(i)* polymerisation from microemulsions of precursor molecules, *(ii)* formation from preformed polymers via microemulsions or precipitation or *(iii)* from naturally occurring polymers such as **polysaccharides** and proteins.

11.5 Analytical applications

The desire for miniaturised sensors is driven by the ever increasing requirement for information to quantify almost all aspects of human endeavour and is especially true in medical situations. The demand for real-time information for efficient control of processes dictates *in situ* measurements and therefore sensor-type approaches with small size a common requirement for practical use. Nanotechnology impacts upon this situation via *(i)* the microengineering of sensors (see section 9.4) and *(ii)* in the design and control required at molecular scales to transduce measurable parameters into easily detectable, typically electronic, signals. The latter item is fundamental to biological applications such as biosensors.

- Biosensors

Biosensors exploit the exquisite selectivity exhibited by biological systems that enables the recognition of one molecular species in the presence of complex mixtures of other, often closely related molecular species found commonly in sample matrices. The integration of biological systems, typically enzymes and antibodies, with suitable physical transducers enables the transduction of biorecognition events into measurable signals. The details of this last point requires design and control at the nanometre scale. For example, systems based upon **enzymes** that perform oxidation and reduction reactions - redox enzymes - such as glucose oxidase for the determination of blood glucose levels, require the efficient communication of electrons generated at the enzyme's active site during the recognition and catalytic events to an electrode for measurement. Various approaches are being developed to enable direct electronic communication between the active site and electrode [100] with "**molecular wiring**" a leading example [101]. The means of integration of the biological component of biosensors is central to their eventual performance and advances in surface science such as self-assembled systems (see section 11.1) are being actively investigated to ease production of devices, increase device stability, reduce interferences and maximise signal output.

- Biochips and high-density sensor arrays

Many examples exist where large numbers of individual biological analyses, *i.e.* **biological assays**, commonly 10^3 to 10^6, need to be performed and include the screening of libraries of potential pharmaceutical compounds and various protocols for the screening and sequencing of genetic material. Such large numbers dictate the parallel processing of assays to enable completion in reasonable timescales and the common availability of only small sample quantity dictates small size. Thus microfabricated high-density arrays of biosensor-like sensor elements have been investigated where the size of individual elements approaches the nanotechnology domain. Such approaches are often termed "biochips" generally meaning an integration of biology with microchip type technologies (Fig. 36). For example, devices are being developed for genetic screening that contain two dimensional arrays with greater than 1 x 10^5 elements each comprising a differing DNA sequence and where each element is optically examined for specific interaction with complementary genetic material [102].

Fig. 36 here

- Other microfabricated bioanalytical systems

The use of microfabricated structures within biological applications are mainly directed towards analytical measurements and often for those that require multiple steps and complex liquid handling. Thus microfabricated systems have been investigated to *(i)* determined the quality of sperm and to perform *in vitro* fertilisation [104], *(ii)* perform DNA analysis by a combination of polymerase chain reaction (PCR) and electrophoretic separation of the resultant amplified DNA [104] with applications including rapid detection of genetic mutations in medicine and DNA typing in forensics and *(iii)* the characterisation and separation of cells using dielectrophoresis and microfabricated electrode and microfluidic structures [105] with potential applications in the detection of food and water-borne pathogens and the separation of human cell types in medicine.

11.6 Other biological applications

- DNA-based computing

A novel technological application of nanoscale biology is the recent demonstration of DNA-based computing [106] where the tools of molecular biology were used to solve a mathematical problem. The problem was encoded in the sequences of DNA molecules, with the operations of the computation performed by the self-assembly of complementary DNA sequences and the answer output by characterising the resulting self-assembled DNA, *i.e.* hybridised DNA, with standard molecular biology tools. Although the calculation required days of laboratory work, the parallel nature of the "computation" and scale-up possibilities suggest further developments will be achieved [107].

- DNA construction sets

The ability of DNA molecules to hybridise to complementary molecules and modern molecular biology's ability to synthesise known DNA sequences has led to the demonstration of DNA as a molecular construction set [108]. Sequences have been designed that spontaneously self-assemble into geometrical structures such as cubes and octahedra. This approach demonstrates a molecular framework or scaffold that could be used to assemble other entities in a defined spatial arrangement at nanometer scales; is this a precursor of artificial nanomachines?

12 National and international activities and initiatives

12.1 National programmes in Europe

Studies undertaken in **Germany** and the **UK** have highlighted the emergence of nanotechnology as a major technological development with a likelihood of having a major economic impact in the medium to long term [109, 110]. Although nanotechnology was not explicitly identified in the UK study, a number of key nanotechnology areas were indicated. These included sensor technology, drug delivery systems and the requirement for new cost-effective nanofabrication processes.

The **UK** launched a National Initiative on Nanotechnology (NION) in 1986 to: a) represent and coordinate government, industrial and academic interests in nanotechnology, and b) to advise Government in all aspects of nanotechnology. A subsequent LINK Nanotechnology Programme (LNP) ran from 1988 -1994 and was closely associated with NION. The programme supported 27 projects, with a government funded budget of around US$ 18 million, with matching funds from industry giving a total of approximately US$ 40 million. The topics covered were:

- ultra precision machining and surface finishing
- nano positioning and control
- nanometrology
- nanostructures
- surface treatment and analysis
- ultra fine ceramic powder materials
- medicine
- biosciences
- micromechanics

The programme was successful in bringing together universities and industry to work collaboratively on the above mentioned topics. The NION programme concluded with a 'technology transfer' phase implemented primarily by Cranfield University (UK).

Since 1994 when research councils, within the UK, were re-organised the Engineering and Physical Sciences Research Council (EPSRC) has funded some projects within its own Nanotechnology Programme, and these will be completed in 1999. The Government contribution to this programme was US$ 7.5 million, and major successes, to date, include [111]:

- ultra precision 'ductile' mode grinding of brittle materials, with extremely low levels of sub surface damage
- nanoparticles and in particular a 'world leading' zirconia powder for the fabrication of toughened zirconia ceramics etc
- direct experimental observation of diamond growth mechanisms
- the realisation that, in the field of biosciences, nanotechnology can be regarded as a 'toolbox' for cellular engineering.

The UK Government's Technology Foresight Panels have recently identified technologies which fall in the context of nanotechnology. For example two of the panels ('Information Technology, Electronics and Computing', and 'Defence and Aerospace') identified semiconductor manufacture, sensors, computer peripherals, display devices, mobile communications and micromechanical devices as being areas in which nanotechnology is considered as a fundamental 'enabling' technology. The Materials Panel micromaterials systems, fullerenes, bioelectronics and bioengineering in a similar way. Nanotechnology was also considered to be an important wealth creating technology by the Construction Panel. However the specific areas identified (e.g. conventional materials with unconventional properties) were considered to need long term programmes and to be at least 10 years from commercial exploitation.

Several **German** research institutions are running programmes in key areas of nanotechnology, even though the country does not have any specific nanotechnology programme, as in the UK, to raise industrial awareness of its technological potential. The German Government is funding nanotechnology related programmes in 14 Fraunhofer Institutes together with other universities and industrial research organisations. In addition a Government Microsystems Technology programme, with an annual budget of around US$ 60 million is being funded until 1999.

A recent Delphi study carried out in Germany predicts that the time of realisation of technologies associated with nanometre size structures will be as indicated in Table 4. [112]

Technology	Time of realisation
Processing technology for supersmooth metal mirrors	2002
STM or AFM for analysing molecular structures	2003
Widespread use of atomic layer etching in semiconductors	2004
Embedding impurities and repairing silicon surfaces with STM	2004
Polymer processing for controlling nanostructures in 1 to 10nm size	2007
Mass production of new materials constructed by using ions and particle beams with controlled characteristics	2010

Table 4 - Estimated time to realisation of nanometre size structures - German Delphi study [114]

France has recently formed the 'Club Nanotechnologie' which has brought together many industrialists and academics to identify areas which have national strategic importance. In addition one of the country's seven interdisciplinary government funded programmes, Ultimatech, is aimed at the development of advanced technologies and instrumentation for making nanoscale structures.

Other European countries undertaking Government funded programmes in nanotechnology areas include:

(i) **Italy**, which has a government funded programme in nanotechnology aspects of biotechnology at the Elba Foundation.

(ii) The **Netherlands** Foresight Committee reported recently that nanotechnology research was generally founded on single disciplines and suggested that in future the possibilities of stimulating interdisciplinary research in nanotechnology should be explored [113]

(iii) **Russia** is reported to have several individual groups working on molecular/bio-electronics [114] and other aspects of nanotechnology.

(iv) **Switzerland** has a national research programme which includes chemistry and physics of surfaces, as well as more general nanotechnology activities, e.g. scanning probe microscopy notably at the IBM Research Laboratories, Zurich.

12.2 USA

As with other major technologies, progress in nanotechnology is being pushed in the main by industry, and in particular the larger firms. However Government funding bodies supporting micro engineering, especially Micro-Electro-Mechanical Systems (MEMs) are:

a) the Advanced Research Projects Agency (ARPA) (US$ 40 m pa,
b) the National Science Foundation (NSI) (US$ 5 m pa), and
c) the National Institute of Standards and Technology (NIST) (US$ 5 m pa).

In addition the US Department of Defence Initiative on MEMs funded special 'sensitive' projects with US$ 46 m in 1996 and this has risen to US$ 63 m in 1997.

Thus the main activities in USA micro and nanotechnology programmes are:

(i) MEMs which encompasses all microsystems technologies and devices
(ii) Nanofabrication for manufacturing devices with nanometre scale structures, and,
(iii) Aspects of the traditional science base (e.g. physical, chemical and biology) appropriate to'nanoscience', including biotechnology.

A National Nanofabrication User Network (NNUN) has been established by in which a key aspect is aimed at bringing together key industrialists and academics to create an 'environment of self help'. A core group of successful projects in the areas of biology, chemistry, medicine and physics are presented in appropriate forums. The NNUN has a hub of 2 user facilities available, one on the east coast (Cornell University) and one on the west coast (Stanford University). In addition three additional sites offer expertise in the specific areas of a) wide band semiconductors (Howard University), b) novel materials (Pennsylvania State University, and c) semiconductor etching (University of California Santa Barbara).

Centres of excellence in nanotechnology and micro engineering exist at MIT, and the universities of Stanford (California), North Carolina (Charlotte and Raleigh) and California (Berkeley).

Dr Eric Drexler (see section 2.4) is President of the Foresight Institute (Palo Alto, California), whose mission and fundamental goal is the "betterment of the human condition, especially as it is related to molecular nanotechnology". The Institute runs regular molecular nanotechnology conferences and publishes 'Foresight Update' to promote an understanding of nanotechnology, and report on worldwide nanotechnology activities.

12.3 Japan

The importance placed, by the Japanese Government, on nanotechnology can be judged by the large amount of government funding it has and is continuing to provide. Funding is made available by 3 separate ministries: Ministry of Trade and Industry (MITI), Science and Technology Agency (STA), and the Ministry of Education.

In 1992, MITI started a major 10 year project 'Research and Development of Ultimate Manipulation of Atoms and Molecules' with total government funding of the order of US$ 250 m. The research consortium currently includes 26 Japanese and 4 foreign companies and the broad range of applications expected to emerge from the programme range from computation e.g. higher density computer memory, to new materials, gene manipulation and new catalysts for environmental clean up.

A further large 10 year project funded by MITI to over US$ 200 m is in the field of 'Micromachines'. Twenty eight companies and institutions, including 3 foreign groups are involved in the programme which is undertaking research in sensors, actuators, energy supply, system control and to bring into being a prototype **micro factory**, one in which very small machines are grouped within table top dimensions for the manufacture of very small (millimetric and sub millimetre) industrial products.

STA Projects have focused on various aspects of nanotechnology over recent years, including **Nano-Mechanisms** (1985-90), Solid Surfaces (1985-90), **Molecular Dynamic Assembly** (1986-91), and more recently the **Atom Craft** project (1989-94) which is investigating the behaviour of atoms and molecules on surfaces and techniques for precision deposition, based upon the application of STM technology. STA is also responsible for the Institute of Physical Chemical Research (RIKEN), which ran a **'Frontier Research Programme'** in the areas of molecular electronics, bioelectronics, and quantum electronics. One objective of this programme is the development of an 'artificial brain'. The Ministry of Education supplies research funding for universities, and this includes several nanotechnology programmes.

The Applied Technology Development Department within Japan's New Energy and Industrial Technology Development Organisation (NEDO) has several current nanotechnology and microengineering related projects which are undertaking research and development aimed at:

a) medical applications (micromachines capable of undertaking advanced coeliac diagnosis and treatment with minimal damage to the human body),
b) electronics, information and communications (including quantum functional devices to realise ultra high speed and ultra functional information processing technologies), and
c) biotechnology (molecular assemblies for functional protein systems and evolutionary molecular engineering).

12.4 Europe - collaborative

There are no formal nanotechnology programmes funded by the European Commission (EC) although there are several programme areas in which nanotechnology is highly relevant. For example, protein engineering, biosensors, etc. are included in the Biotechnology Action Programme. The current BRITE/EURAM programme in Materials Science have identified 17 projects which involve nanotechnology [114] as well as others in the area of 'microtechnology'. Nanotechnology is also a part of the Biomedical Technology Programme, e.g. artificial limbs, nerves, hearing, sight, etc. [115].

Within the 4th Framework Programme, running from 1994 to 1998, which supports Microsystems Technology, a microsystem is defined as 'an intelligent miniaturised system comprising sensing, processing and/or actuating functions, normally combining two or more electrical, mechanical or other properties on a single chip or multichip hybrid'. The EC has made available around US$ 33 m for an ESPRIT Advanced Research Initiative in Microelectronics.

Other EC funding has been directed towards the establishment of micro and nanotechnology networks to support research and development to improve European competitiveness. Networks of Excellence which bring together relevant industrial and academic research groups, are aimed at bridging the cultural differences that exist between European Countries. Three relevant Networks of Excellence funded by the EC are:

(i) PHANTOMS which is coordinating work on Mesoscopic Physics and Technology. The research covers the areas of nano-electronic components, nanotechnology fabrication, opto-electronics and novel architectures for switching. There are 18 partner countries in this programme.

(ii) NEOME (Network Excellence on Organic Materials for Electronics) has run since 1992 and is coordinating work in the area of organic materials for electronics as the basis for nanostructures, optical devices, electro-optical switches, sensors and for potential applications in information storage and information processes. Ten countries are currently directly involved in this network.

(iii) NEXUS (European Network of Excellence in Multi-functional Microsystems) was established in 1992. Its brief includes:

  a) coordinating work in microsystems technology (MST),
  b) the strategic assessment of international MST developments, and
  c) the formation of links to small and medium sized enterprises.

Other Networks include:

(i) EUROPRACTICE which has been established to stimulate the exploitation of state-or-the-art microelectronics technologies by European industry to improve industrial competitiveness.

(ii) NANO to coordinate research and development in nanostructured materials.

(iii) INPEC, an international network of protein centres, which is concerned with information exchange between countries, related to changing and studying the properties of molecules.

A proposal is being submitted to the EC during 1997 for the establishment of the European Society for Precision Engineering and Nanotechnology (EuSPEN). The Society aims to strengthen industrial and research potential in precision engineering and nanotechnology by establishing a society, organising events, initiating transnational research projects, building a comprehensive database and helping develop education and training programmes in precision engineering and nanotechnology. The EuSPEN Foundation Committee comprises one industrialist and one academic from 6 countries, namely Denmark, France, Germany, Italy, The Netherlands and the UK.

12.5 Rest of the World

Two other countries investing in nanotechnology related areas are **Taiwan** and **South Korea**. Taiwan has had a strong IC industry since the mid 1980s and research is being funded, through the National Nano Device Laboratories, in the area of ultra-large scale integrated circuits. The research started with 250nm feature sizes but is now concerned with lower feature sizes of 180nm and intends to progress to smaller scales. **Taiwan** is also strong in the area of information technology and is now the main producer of 'merchant motherboards' for personal computers.

South Korea has strong government funded programmes in microelectronic and precision engineering which are starting to bear fruit. For example, companies such as Samsung, are currently producing advanced flat panel displays dependent on nanotechnology production processes.

13 The effect of nanotechnology on world development

13.1 World markets

There are huge potential markets for nanotechnology related products. For example in areas such as semi-conductors, computer peripherals, bio-medical engineering and pharmaceuticals the potential markets are US$ multi-billions in each case [115]. Because of the wide diversity of products which can be considered as being in the nanotechnology domain it is difficult to accurately predict future potential markets. However in 1994 the German Ministry for Research and Technology produced a detailed estimate of the market potential for what they considered to be specific nanotechnology products - see Table 5 [116]. This shows the largest area to be for devices using lateral structures, e.g. microelectronic components, precision nozzles and filters, micro sensors and some optical components. Table 5 also indicates the ascendancy of ultra precision engineering.

Table 5 Global market potential US$ bn

TECHNOLOGY	1991	1995	2000
Thin films	9.2	13	18
Lateral structures	70	139	223
Ultra-precision engineering	5.2	9.7	18.2
Nanocrystals	0.05	0.08	0.11
Nanometrology	0.62	0.83	1.1

Source: VDI Germany [116]

It is easier to assess individual product potential. For example, one German company has patented a micro-fabricated CFC-free nebuliser, and estimates that it has a global market potential of US$ 6.4 bn p.a. Another product - the air bag sensor, which currently costs around US$ 160, is set to be replaced by mass produced sensors costing around US$ 5. The global market potential for MST (microsystems technology) products has been quoted, from several sources, as being set to reach US$ 25 bn by the year 2002 [115].

13.2 Research and development

The high cost of developing marketable products from basic research findings dictates that it will involve mainly larger firms. However small and medium sized firms are often best suited to serve the niche market areas, although this might be limited by the large capital investment required. To counteract this the successful USA 'Small Business Innovative Research' programme is making available high risk venture capital for high technology (including nanotechnology) start ups. However, there is little evidence of similar programmes being initiated in Europe or elsewhere. The international trend in funding research and development appears to be directed more toward short term competitive application oriented research, which in turn could reduce the funds available for more basic longer term research. Examples of research and development which are needed to extend microengineering and nanotechnology include:

(i) Materials and Processes: the integration of these areas is essential, as methods of forming parts will require additional techniques which allow the efficient removal or accretion of material down to the atomic scale.

(ii) Mechanisms and Structures: the microscopic tools and motions require the research, design and manufacture of fine mechanisms which can accurately position and manipulate objects of appropriate scale. Critical analysis of microstructures e.g. stability, friction, wear, chemical, electrical and magnetic properties is needed.

(iii) Nanometrology: the successful application of nanotechnology depends upon the ability to accurately measure minute displacements. Examples of specific research includes longer range X-ray interferometry, providing picometre resolution and 'absolute' interferometry based on multi-wave length solid state lasers and sensors.

13.3 Opportunities for exploitation

Drexler predicts [117] that developments in nanotechnology will result in the production of nano robots that will be able to reproduce themselves and clean up the environment, repair damaged living tissue, etc. However this is thought, by many experts, to be very futuristic and that more realistic opportunities for exploitation lie in advancing the capabilities of products such as microprocessors, disc drives, display devices and printers, etc. Further areas for exploitation include minimally invasive surgery tools, sensors for environmental and automotive application, and medical diagnostic and analysis tools. Many observers see nanotechnology as being a key technology to ensure competitiveness, into the 21st century, for a wide range of products. Likely future application of 'nanotechnology' products are shown in Table 6.

Table 6 Likely future applications of nanotechnology

Product	Comment
Micro/macro optics (including fibre optic devices)	Improved telecommunications
Prosthetic devices	Lighter, cheaper, longer life, - increased functions
Catheter based medical diagnostics	Improved imaging systems and analysis
Micro surgical devices	Therapy systems and micro surgery non-trauma surgery; faster wound healing; efficient drug targeting in the body
Medical diagnostics, using colloidal particles	Blood sampling in ante-natal care and cancer screening
Photonic products	Miniaturisation
Micro filters	Many environmental applications
Micro optical systems	High speed beam positions. Scanning shutters
Compliant and active probe micro-assays	Applicable to micro electronic manufacture, biological and neural investigation
Micro switches	Faster operation, lower power consumption
Deformable structures	Valves, micropositioning analogues of muscle
Semi-solid fuel injectors	Cost and control low weight
Mass storage	Even denser packing, higher speed devices
Inks incorporating colloidal nanoparticles	Ink jet printers
Automotive components (pistons, camshafts, crankshafts, etc)	Improved wear, life and reduced environmental pollution
Advanced optics (including aspherics) and opto electronics	Improved performance, smaller and cheaper
Nanofabricated surface coatings	Coatings for keeping windows clean; protective 'skins' for many applications
Thin film sensors and actuators	Environmental monitoring and nano-manipulation
High resolution display systems	Using quantum well technology, or based on molecular structures

13.4 Developing countries

The high cost of establishing nanotechnology research and development programmes will undoubtedly severely limit activities in developing countries, for the foreseeable future. However the technology and products arising from programmes in developed nations will have many important applications in the developing countries, as well as elsewhere. Thus developing countries may wish to have well qualified scientists and engineers further educated and trained in nanotechnology so that they can advise their governments on priorities in applications - and later, developments in their own countries (see 13.5 below).

Appropriate applications include controlling and cleaning the environment and improving healthcare. Cheap sensitive and accurate sensors are emerging for monitoring the atmosphere and water quality, and opportunities exist to apply biological 'machines' to clean up the environment by the extraction of pollutants. In the area of healthcare nanotechnology is enabling minimal invasive surgery and effective drug delivery systems. Research programmes are targeting intravenously administered drugs to different organs, such as the lung, liver, spleen, sites of inflammation and to tumours [118]. These drugs, coated with antibodies, resist attack by the body's own defence cells, and can lock on to the appropriate target such as a tumour, thus avoiding the release of toxic drugs on healthy tissue. New developments, taking account of economic and social factors are placing an emphasis on prevention rather than corrective medicine and surgery.

13.5 Needs for education and training

Nanotechnology demands multi-disciplinary inputs from scientists and engineers and recognition is needed with regard to the important role of education, in maximising the future wealth creation possibilities. The necessary advanced skills in this heavily science based area can only realistically be developed through intensive, multi-disciplinary postgraduate courses. The education and training of young physicists, mathematicians, chemists, materials scientists and engineers is essential in order to ensure a flow of high calibre postgraduates into industry. Never before have these been at such a premium and those nations and the postgraduate courses which harness these skills will surely reap large benefits.

Nanotechnology Centres of Excellence within UK universities are given in Table 7 below [115].

Table 7 Nanotechnology - University Centres of Excellence in the United Kingdom

Organisation	**Principal Areas**	**Organisation**	**Principal Areas**
Birmingham University	nanoparticles; surfaces nanostructured materials	Imperial College	MST/microsystems
Cambridge University	microelectronics; energy beam processes	Nottingham University	semiconductors, bio-physics, pharmaceuticals
Cranfield University	precision engineering; engineering nanotechnology; nanostructured materials biosensors and nanobiotechnology	Southampton University	silicon fabrication
Glasgow University	nanoelectronics nanobiotechnology	Warwick University	precision engineering; nanometrology
Heriot Watt University	microsurgery		

14 Conclusions

The authors of this paper have set out to explain what nanotechnology is, to describe the current state of the art, emphasise its essential multi-displinary nature and convey the enormous impact it will progressively make on product and process research and thence on to manufacturing technologies, industry and the economies of countries throughout the world. Undoubtedly, nanotechnology is a major, new technological force destined to have major socio-economic effects. It promises many benefits in standards of living and quality of life.

The authors hope that they have succeeded in making the topic interesting and informative to a wide readership from those with curiosity and a limited scientific base to scientists and engineers some of whom may be stimulated to engage in further study.

For developing countries, the high cost of nanotechnology R&D will severely inhibit such activities being developed for the foreseeable future. However, nanotechnology products will have many important applications in developing countries as elsewhere such as environmental clean-up, water quality improvement and health care. Across the world, successful nanotechnology developments will depend more and more on education and training. Owing to the very wide range of disciplines and thus the breadth of understanding needed, the necessary skills in this heavily science-based, technological thrust can be developed, only through intensive, multi disciplinary post-graduate courses, closely related to social and industrial needs.

The evolution towards the 'Nanometric Age' is gathering pace. It has the potential to provide revolutionary benefits.

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GLOSSARY

1. **Accretion** - growth or increase by the additive assembly of atoms or molecules.
2. **Capacitance gauge** - non contact measuring device that determines the distance (gap) between a probe and the target surface, by measuring changes in capacitance.
3. **CBN** - cubic boron nitride, the second hardest man-made material after diamond. Unlike diamond, it will resist chemical attack by iron during machining.
4. **CNC** - computer numerically controlled.
5. **'Ductile regime' grinding** - see 'shear mode' grinding.
6. **Eddy current probe** - non contact measuring device that determines the distance (gap) between the probe and the target surface, by measuring changes magnetic fields generated by eddy currents in the surface.
7. **Frequency Tracking Fabry Perot Etalon** (FPE) - device to measure and compensate for variations in the refractive index of air i.e. temperature, pressure and humidity.
8. **Interferometry** - technique of dividing a beam of light into a number of beams and re-uniting them to produce interference fringes. Uses include the accurate determination of wavelengths of light, displacement and velocity.
9. **Laser interferometer** - very accurate displacement measuring system; many current systems use the wavelength of helium-neon laser as a measuring standard. (See also OHI)
10. **Linear variable displacement transformer (LVDT)** - displacement measuring contact probe which employs electromagnetic induction to sense linear motion; can have sub-nanometre resolution.
11. **Metrology frame** - a stationary reference frame, uncoupled from the machine structure, by which the tool or probe position of a machine are measured with respect to the workpiece.
12. **Optical grating scale** - linear displacement measurement device which operates on the principle of counting and sub-dividing scale lines with the use of a light source and photodiodes.
13. **Optical Heterodyne Interferometry (OHI)** - two frequency laser, used in most laser interferometers
14. **Piezoelectric material** - a material whose crystal structure lacks a centre-of-symmetry and which will generate electrical charges when stressed. Conversely, it will undergo mechanical strain when subjected to an electric field in which the strain is proportional to the applied field.
15. **'Shear mode' grinding** - a grinding technique for machining hard and brittle materials with a 'continuous' type chip and with zero or minimum sub-surface damage.
16. **Vapour deposition** - a surface coating process in which the workpiece surface is subjected to chemical reactions by gases that contain chemical compounds of the material to be deposited.
17. **Transmission Electron Microscope (TEM)** - a microscope which uses electrons transmitted through the specimen rather than light. The electrons are focused (in a similar manner to light in an optical microscope) using electromagnetic lenses.
18. **Scanning electron microscopy (SEM)** - a microscope which uses a focused spot of electrons scanned across the object under study. The image is formed by collecting electrons or X-rays scattered from, or produced by, the object under study.
19. **KeV - Kiloelectron volt** - the energy attained by an electron when it accelerated by a potential differences of 1000 volts.
20. **Evanescent Wave** - a wave whose amplitude decays exponentially with distance into a medium.
21. **Scanning Probe Microscope (SPM)** - a microscope which uses a probe scanned in two dimensions across the surface of an object to be studied and which forms an image through an interaction between the probe and the surface.
22. **Scanning Tunnelling Microscope (STM)** - A SPM in which the probe is a sharp conducting tip and the interaction is a tunnelling current generated as a consequence of an electric bias.
23. **Scanning Noise Microscopy** - A STM in which the tunnelling current is explored without an electrical bias field by means of the broadband r m s noise.
24. **Scanning Tunnelling Potentiometer** - A STM in which an a c signal is used to generate a constant top-to-sample spacing.
25. **Radio-frequency** - an electromagnetic signal with a frequency between 100 KHz and 1 GHz.
26. **Atomic Force Microscope (AFM)** - a SPM which uses the Van der Waals attraction between a tip and the substrate as the probing signal.
27. **Magnetic Force Microscopy (MFM)** - a SPM which uses a magnetic tip and the magnetic forces between the tip and the substrate as the probing signal.
28. **Electrostatic Force Microscopy (SFM)** - a SPM which uses electrostatic forces between the tip and the substrate as the probing signal.

29. **Scanning Thermal Microscopy (SThM)** - a SPM which uses a tip (such as a piece of Wollaston - PtRh alloy - wire) capable of generating a thermal signal and detecting a temperature change.
30. **Scanning Near Field Optical Microscopy (SNOM)** - a SPM which uses an evanescent optical wave emerging from a drawn optical fibre as the probe.
31. **Semiconductor** - a material in which the valence band is filled and conduction band empty. Conduction is dominated by electrons in the conducytion band or holes in the valence band due to the presence of impurities acting as either electron donors or acceptors.
32. **Chip** - a semiconductor device with 2 or more active devices (e.g. transistors) defined on it and connected together.
33. **Mbit (Megabit)** - a million (10^6) bits of information.
34. **Gbit (Gigabit)** - a billion (10^9) bits of information.
35. **Photolithography** - the use of light to transfer the pattern from a mask to a polymer resist on the surface of a wafer.
36. **Ultraviolet (uv)** - light with a wavelength between approximately 450 and 100 nm.
37. **Mercury "g" line** - uv light with a wavelength of 436 nm.
38. **Mercruy "i" line** - uv light with a wavelength of 365 nm.
39. **X-ray lithography** - the use of X-rays to transfer a pattern from a mask into a polymer resist on the surface of a wafer.
40. **Electron beam lithography** - the use of a focused electron beam to define a pattern in a polymer resist on the surface on a wafer.
41. **Synchrotron radiation** - the radiation emitted by high energy electrons confined to circulate in a ring as they are accelerated around a curve.
42. **Microsystem** - a device consisting of sensors and actuators integrated together with a semiconductor signal processing capability in a single micro-assembled package.
43. **Micro-electro-mechanical systems (MEMS)** - see "microsystem".
44. **Microsystems Technologies (MST)** - the technologies for making microsystems.
45. **Micromachining** - techniques for making three dimensional structures on the micrometer scale on a microsystem.
46. **LIGA (Lithographic, Galvanforming und Abforming)** - the use of X-ray lithography to expose a pattern from a mask in a thick polymer photoresist followed by a replication in nickel using electroplating.
47. **Microsystems engineering** - see MST and MEMS.
48. **Shape memory alloy (SMA)** - an alloy which returns to a pre-determined shape when heated through a martensitic phase transition temperature.
49. **Electrostatic Actuator** - an actuator which exploits electrostatic attraction or repulsion between two charged components.
50. **Electrostrictive Material** - a material which undergoes mechanical strain when subjected to an electric field where the strain is proportional to the square of the applied field.
51. **Ferroelectric Material** - a polar dielectric in which the direction of the polarisation can be switched between 2 or more directions which are related to each other through the symmetry of a higher temperature non-polar (paraelectric) phase.
52. **Lead zirconate titanate (PZT)** - a solid solution between the two compounds lead zirconate ($PbZrO_3$) and lead titanate ($PbTiO_3$) which possesses a crystal structure isomorphous with the mineral perovskite.
53. **Electro-optic effect** - the effect by which a transparent material's refractive indices are changed by the application of an electric field.
54. **Nanostructured Material** - a material which there is some aspect of the structure deliberately defined to be in the nanometre range and which has a useful effect upon the material's properties.
55. **Nanophase Material** - see Nanostructured Material.
56. **Quantum confinement** - the use of nanostructuring in a material to confine the conduction electrons and thus to generate new energy bands.
57. **Quantum wire** - a nanostructured conductor in which the electrons are confined to move in one dimension.
58. **Quantum dot** - a nanostructured conductor in which the electrons are confined in all three dimensions.
59. **Biological assay** - a process to measure or assay a particular biological function.
60. **Chemo-mechanical molecules** - molecules that convert chemical energy in mechanical energy.
61. **Enzymes** - proteins that catalyse various chemical and biochemical reactions.
62. **Molecular wiring** - pathways to enable the transmission of electrons.
63. **Motor protein** - enzymes that convert chemical energy into directed movement of molecules.

64. **Polysaccharides** - naturally occurring polymers of various sugar molecules.

65. **RNA** - a naturally occurring biological polymer, similar to DNA, that encodes information in the sequence of its constituent monomers.

66. **Transcription** - the biological processes by which the information present within DNA (genes) is copied or transcribed into RNA.

67. **Translation** - the biological processes by which the information present within RNA is converted or translated into a specific protein molecule.

Figure Captions

1. Some size scales from human to atomic. (Reproduced with kind permission of 'Chemistry in Britain' and Dr Peter Day)
2. The development of achievable 'machining' accuracy over the last sixty years.
3. Scanning electric micrograph of 'chip' of electroplated copper cut by a sharp diamond on an ultra precision machine tool. The underformed chip thickness is about 1 nm. The resulting surface smoothness is about 1 nm R_a - a super smooth, very high reflectivity surface is produced directly on aluminium, copper, electroless nickel etc without the need for subsequent polishing (Courtesy of Professor J Ikawa, Osaka University)
4. The mechanism of 'ductile' or 'shear mode' CNC grinding of brittle materials; depth of cut d_p must be less than the critical transition depth at which brittle fracture occurs. This demands high precision, high stiffness machine tools and achieves very high surface smoothness with virtually no sub-surface microcracks.
5. The principle of electron beam machining (EDM); high energy electrons are focused electromagnetically onto the target in a vacuum; nanometre patterning accuracy can be achieved.
6. An example of high speed raster scan EDM: 'writing the Encyclopaedia Britannic on the head of a pin'. The line width of each letter is two electron beam drilled holes; each hole is 4 nm diameter; the substrate is silicon fluoride. (Courtesy of Professor C Humphreys, Cambridge University)
7. The principles of ion beam machining; electrically accelerated inser-gas ions such as argon are projected at the target surface in a high vacuum, providing 'atomic-bit' machining capability.
8. Relative control accuracy in repairing an LSI chip line of 4 µm width by focused ion beam (FIB) machining and a low power micro-focused laser. Today's excimer lasers can achieve finer focus and control.
9. Schematic of a scanning tunnelling microscope probe, showing interaction of the electron clouds of the nearest atoms of the probe and object. The probe is moved in the X, Y directions and servo controlled in the Z direction with picometre resolution - to produce a Y scan trace of the surface atoms (topography) of the object
10. The screen image of an STM surface scan showing atoms of carbon; this whole image is approx. 1 nm x 1 nm.
11. SEM image of 35 Xenon atoms on nickel substrate - IBM
12. The Nanotechnology Tree of Commercial Opportunity
13. A 3D error map for a precision machine showing the uncorrected systematic errors in x, y and z directions that can be reduced by software error compensation.
14. STM Design for High Dynamic Stiffness.
15. Tolerance trends in manufacturing with product examples (ref. D.A. Swyt - NIST, USA).
16. Nanometrology: limits for different measurement principles (ref. C Teague - NIST, USA).
17. Principle optical components and operating principle of an optical heterodyne interferometer (ref. A. H. Slocum).
18. Interferometric plot of a sub-nanometre surface finish produced on optical germanium.
19. Schematic of the NIST Molecular Measuring Machine. (Courtesy of National Institute of Standards and Technology, USA).

20. Human hair micromachined, with no discernible damage, by excimer laser mask projection (Courtesy of Exitech Ltd., UK)
21. Resulting shear stress V's chip thickness, showing high stresses with fine machining. (Ref. N. Taniguchi)
22. The 'Electrolytic In-Process Dressing' (ELID) technique, used for 'ductile mode' grinding.
23. Nanocentre: for the direct machining of complex aspheric optics, etc. (Courtesy of Cranfield Precision, UK)
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27. Nanocentre performance in horizontal straightness error motion obtained with the use of a metrology frame and computer software error compensation techniques.
28. 'Moore's' Law, showing the logarithmic increase with time of the number of transistors on memory or microprocessor chips.
29. Schematic diagram of a microsystem.
30. Cairns IRIS pizoelectric thermal imager for fire fighters manufactured by GEC Marconi and marketed by Cairns Inc. (Courtesy of Cairns (UK) Ltd.)
31. A multi layered Ti/TiN coating produced commercially by Multi-arc Ltd shown here a) before and b) after impact by a 600 μm sand particle travelling at 250 ms^{-1} The impact of the particle causes the top layers to form into a tough composite, absorbing energy and protecting the underlying substrate. (Courtesy of Prof. J.R. Nicholls, Cranfield University (UK)).
32. Schematic representation of self-assembled systems showing the molecular arrangement within lipid vesicles and Langmuir-Blodgett films (• represents a polar region of a molecule and —— represents a non-polar, region of a molecule) and within two forms of self-assembled monolayers where R represents a variety of possible chemical groups. The alkanethiols typically self-assemble on gold and similar surfaces while the organofunction silanes self-assemble on oxide surfaces such as silica.
33. Schematic representation of a bacterial flagellar motor that demonstrates a molecular-based rotary motor powered by electrochemical gradients present across the bacteria cell membrane. The motor resides in the bacterial cell wall with the flagellar (hook and filament) projecting out from the membrane and where rotation of the flagellar provides bacteria with propulsion. Various molecular components of the motor are labelled. Figure adapted from [89].
34. Schematic representation (approximately to scale) of the measurement of single molecule intractions. An AFM probe is modified with a biological molecule (streptavidin) and brought into contact with a surface modified with a complementary biological molecule (biotin) and a molecular complex is formed. The ability of the AFM to measure forces, in the range of nanonewtons and less, enables the force required to break the molecular interaction to be measured as the AFM probe is retracted from the surface. The small diameter of the AFM probe limits the number of molecules able to interact to only a few, or even a single molecule.
35. Schematic describing the physical manipulation of a single molecule. In this example a single DNA molecule is attached to a surface and to a 0.5 μm polystyrene bead. The

individual DNA molecule can be stretched by using an optical tweezer to apply force to the bead and hence the DNA. An optical tweezer comprises a focused, high intensity light beam in which gradients of radiation pressure enable the bead to be trapped. Figure adapted from [93].

36. An example of a biochip used for DNA analysis. A schematic of a 4 x 4 array of 16 different DNA molecules (represented by the vertical "ladder" structures) immobilised to a surface. 2 of the array points show interaction with other complementary labelled DNA molecules ("ladders" with •) which can be detected by the presence of the label, *e.g.* a fluorescent label. Scaling to high density arrays of greater than 10 000 array points has been demonstrated and requires the utilisation of microfabrication techniques.

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FIGURES. and Legends.

①

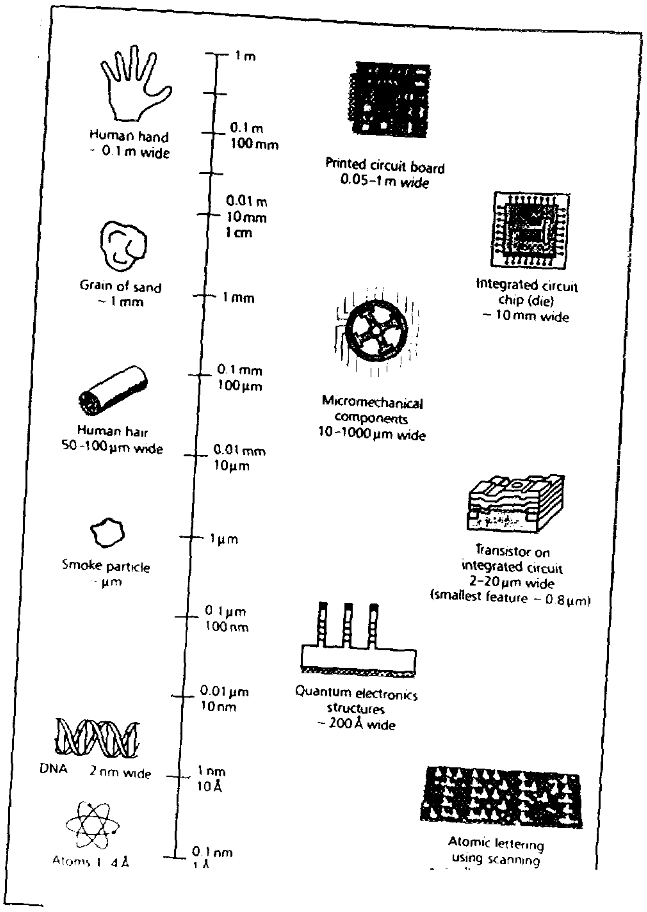
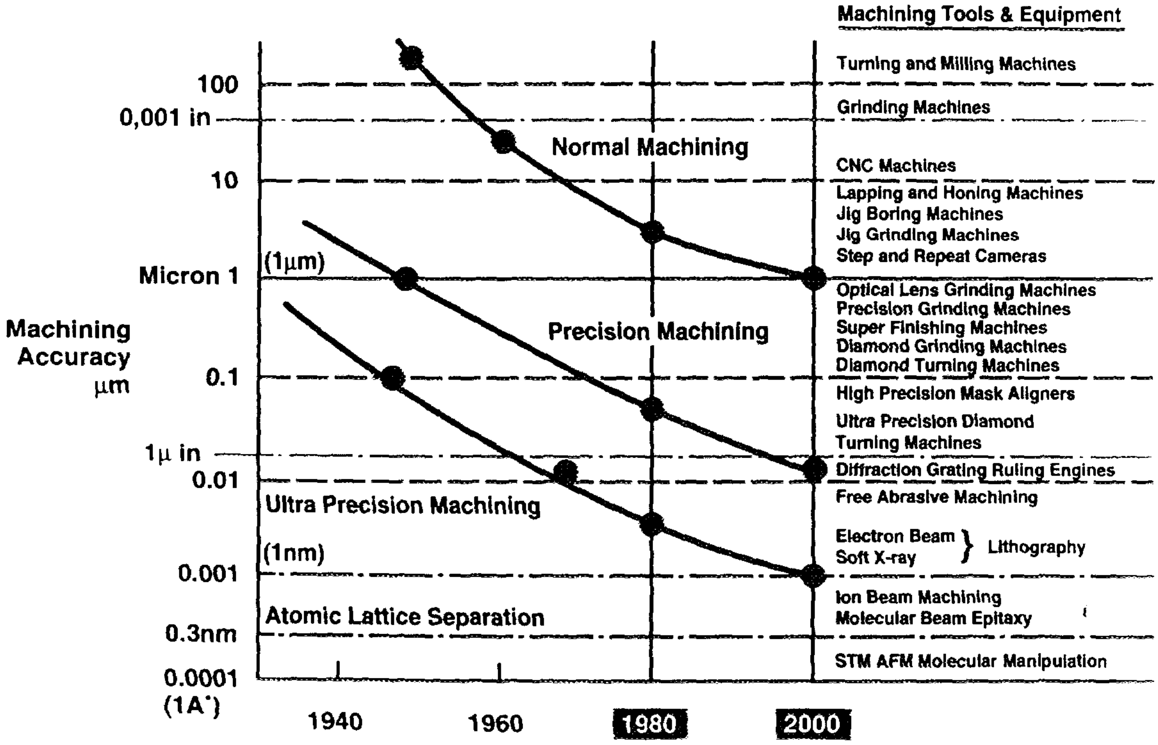


Fig. 1. Some size scales from human to atomic (reproduced with kind permission of 'Chemistry in Britain' and Dr. Peter Day)

ACHIEVABLE 'MACHINING' ACCURACY



* (After Taniguchi)

Fig. 3. Scanning electric micrograph of 'chip' of electroplated copper cut by a sharp diamond on an ultra precision machine tool. The underformed chip thickness is about 1 nm. The resulting surface smoothness is about 1 nm Ra - a super smooth, very high reflectivity surface is produced directly on aluminium, copper, electroless nickel etc. without the need for subsequent polishing. (Courtesy Professor N. Ikawa, Osaka University).

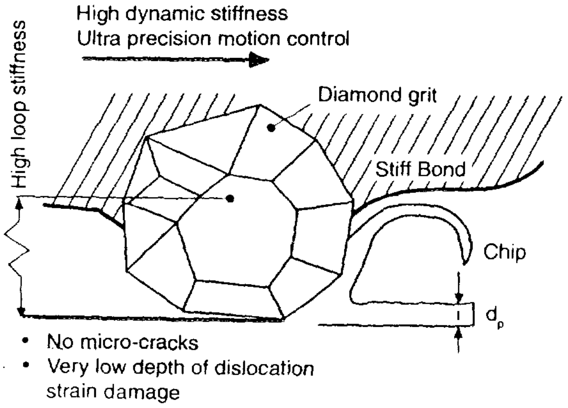


Fig 4. The mechanism of "ductile" or "shear mode" CNC grinding of brittle materials; depth of cut d_p must be less than the critical transition depth at which brittle fracture occurs. This demands high precision, high stiffness machine tools and achieves very high surface smoothness with virtually zero sub-surface microcracks.

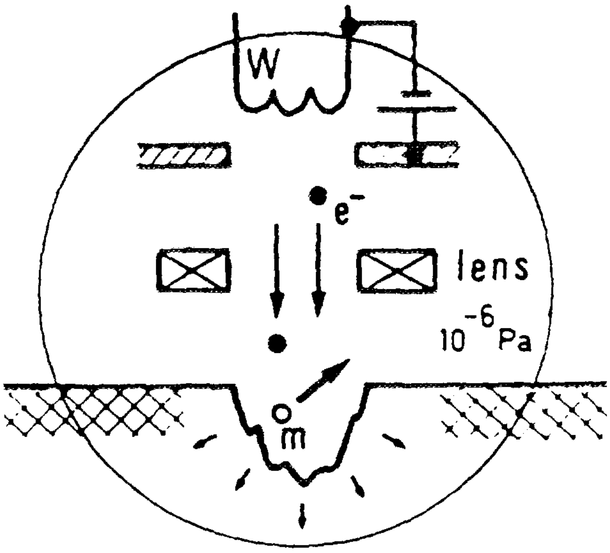
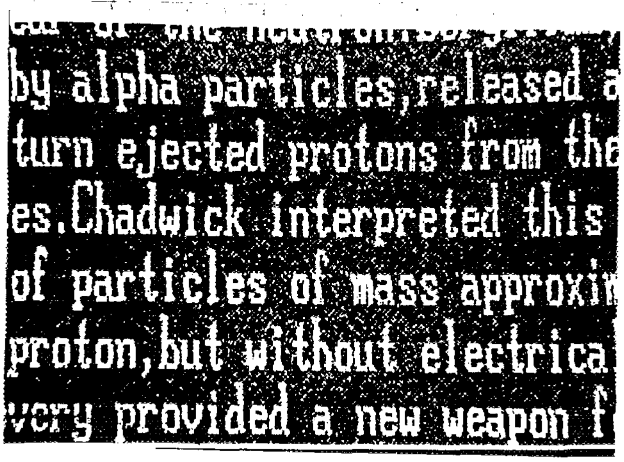


Fig. 5. The principle of electron beam machining (EBM); high energy electrons are focused electromagnetically onto the target in a vacuum; nanometre patterning accuracy can be achieved.



by alpha particles,released a
turn ejected protons from the
es.Chadwick interpreted this
of particles of mass approxi
proton,but without electrica
very provided a new weapon f

Fig 6. **High speed raster scan EBM "writing the Encyclopaedia Britannica on the head of a pin"; the line width of each letter is two electron beam drilled holes; each hole is 4 nm diameter; substrate is silicon fluoride (Courtesy Professor C Humphreys, Cambridge University.**

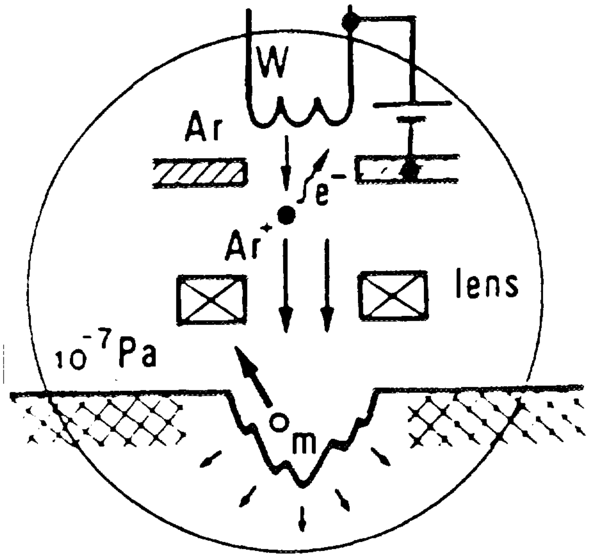


Fig 7. **The principle of ion beam machining; electrically accelerated inert-gas ions such as argon are projected at the target surface in a high vacuum, providing "atomic- bit" machining capability.**

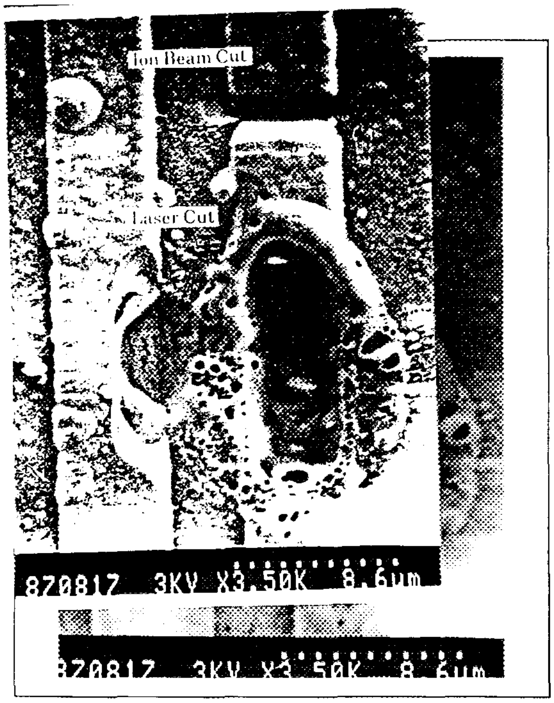


Fig 8. Relative control accuracy in repairing an LSI chip line of 4μm width by focused ion beam (FIB) machining and a low power micro-focused laser. Today's excimer lasers can achieve finer focus and control

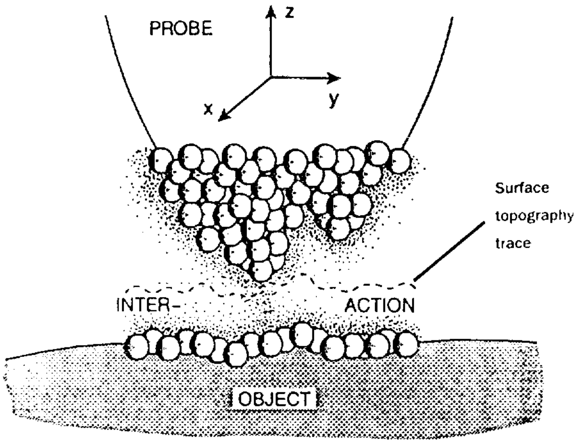


Fig.9. **Schematic of a scanning tunnelling microscope probe, showing interaction of the electron clouds of the nearest atoms of the probe and object. The probe is moved in the X, Y directions and servo controlled in the Z direction with picometre resolution - to produce a Y scan trace of the surface atoms (topography) of the object.**

Fig.10. **The screen image of an STM surface scan showing atoms of carbon; this whole image is approx.** ~~**1 nm x 1nm.**~~ 1nm x 1nm

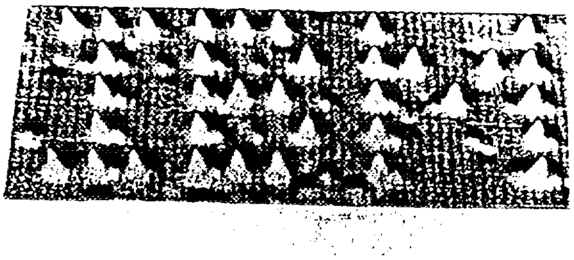


Fig. 11 **SEM image of 35 Xenon atoms on nickel substrate - IBM**

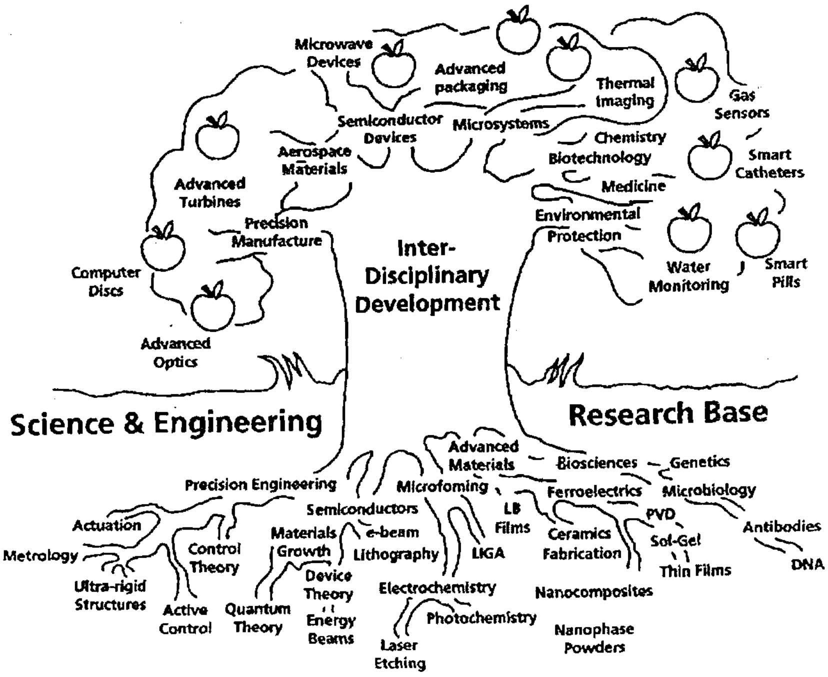
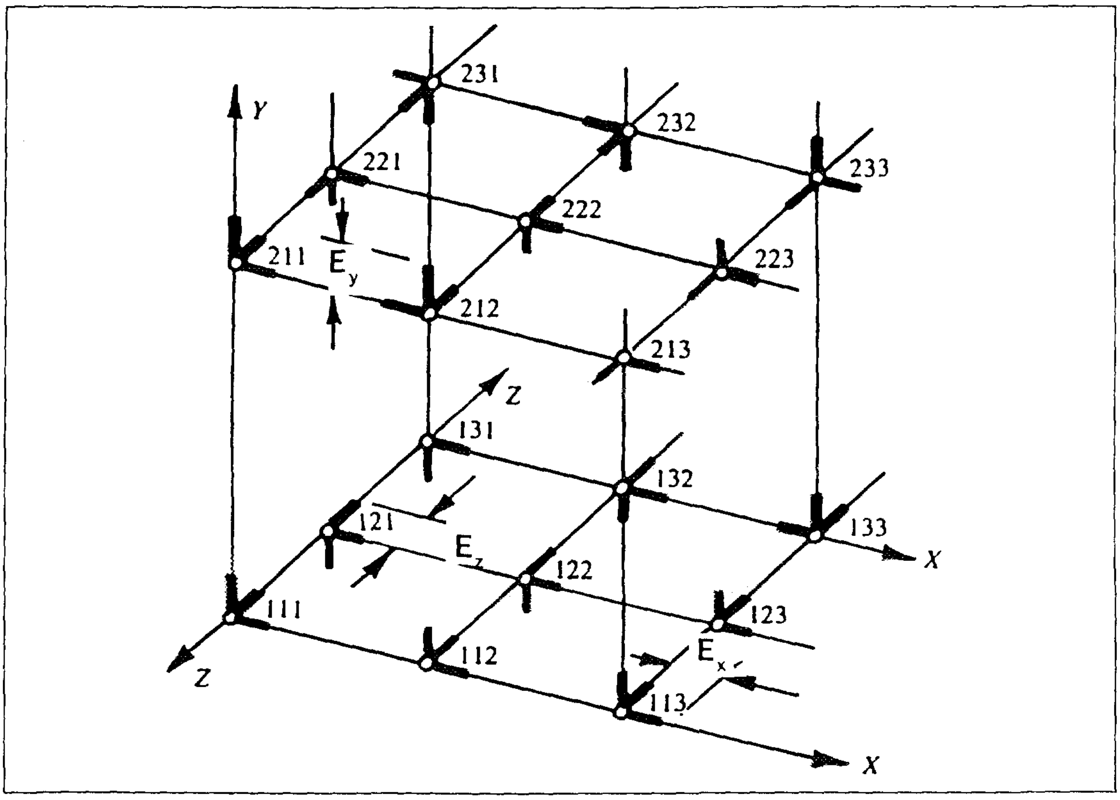


Fig 12



A 3D error map for a precision machine showing the uncorrected systematic errors in x, y, and z directions that can be reduced by software error compensation.

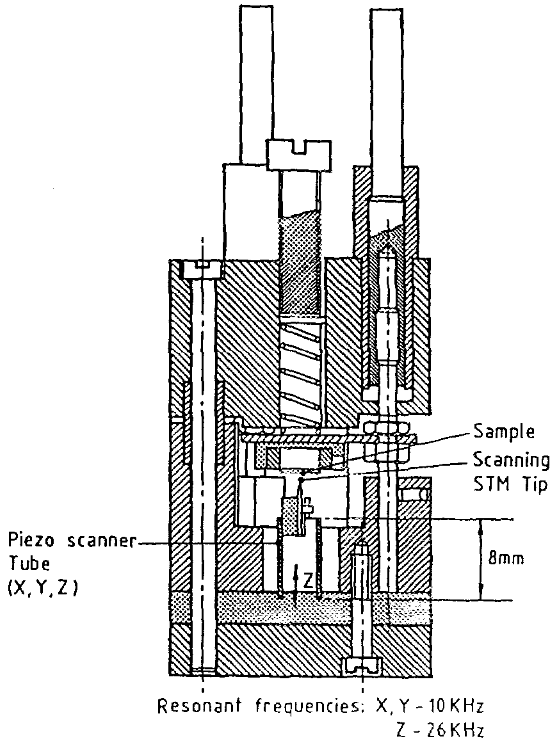


Fig. 14. **STM Design for High Dynamic Stiffness**

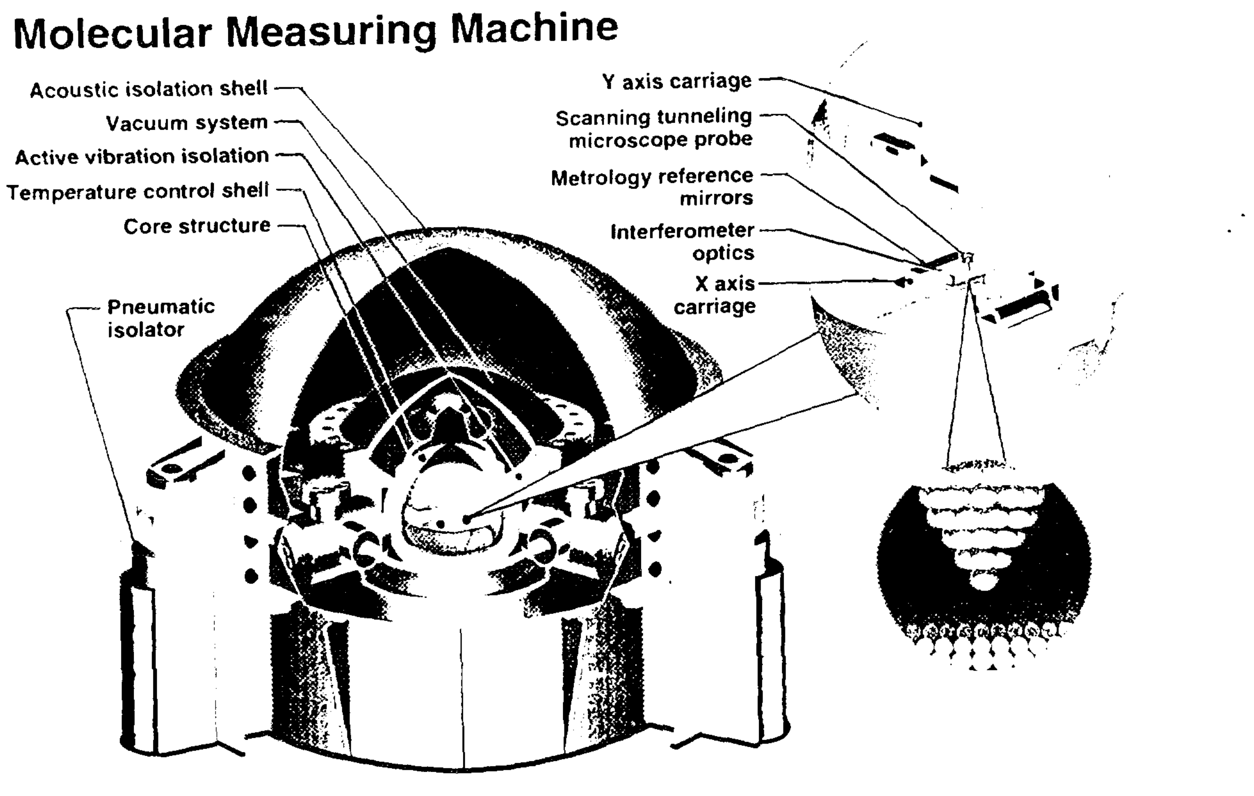


Fig 13. **Schematic of the NIST Molecular Measuring Machine (Courtesy of National Institute of Standards and Technology, USA)**

Fig. 21
Resulting shear stress V's chip thickness, showing high stresses with fine machining. (Ref. N. Taniguchi)

Fig. 22
The 'Electrolytic In-Process Dressing' (ELID) technique, used for 'ductile mode' grinding

Fig. 23
Nanocentre: for the direct machining of complex aspheric optics, etc. (Courtesy of Cranfield Precision, UK)

Fig. 24 Large optics diamond turning machine
(Courtesy of Lawrence Livermore National Laboratory, USA)

Fig. 25
Computer memory disk edge finishing machine for alternative disk materials, e.g. glass ceramic. (Courtesy of Cranfield Precision, UK)

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Nanocentre performance in horizontal straightness error motion obtained with the use of a metrology frame and computer software error compensation techniques

Fig. 18
Interferometric plot of a sub-nanometre surface finish produced on optical germanium

Fig. 19
Supplied by Prof P A McKeown

Fig. 20
Human hair micromachined, with no discernible damage, by excimer laser mask projection (Courtesy of Exitech Ltd., UK)

Fig. 15
Tolerance trends in manufacturing with product examples (ref. D.A. Swyt - NIST, USA)

Fig. 16
Nanometrology: limits for different measurement principles (ref. C Teague - NIST, USA)

Fig. 16
Principle optical components and operating principle of an optical heterodyne interferometer (ref. A. H. Slocum)

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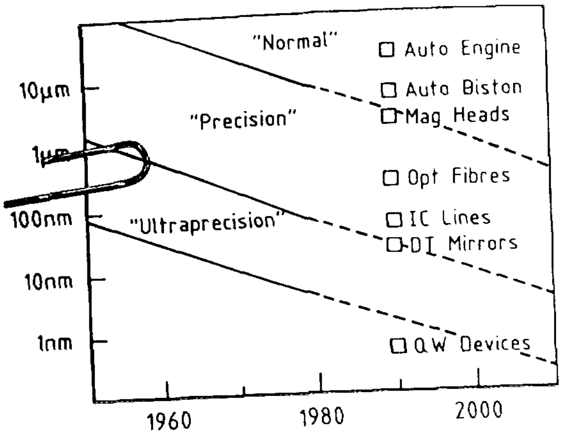


Fig. 15
Tolerance trends in manufacturing with product examples (ref. D.A. Swyt – NIST, USA)

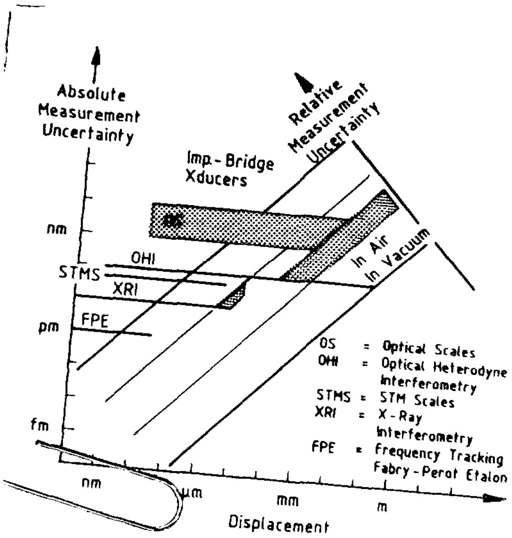


Fig. 16
~~Accuracy limits for differ~~
Nanometrology: limits for diffent ~~measuring~~ measurement principles (ref. C. Teague – NIST, USA)

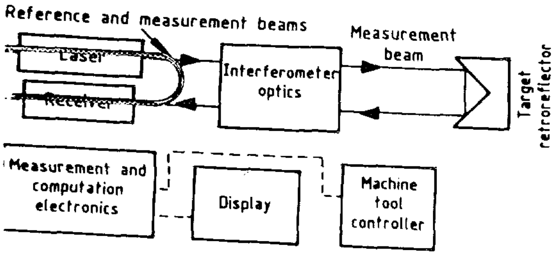


Fig. 17
Principle optical components and operating principle of an optical heterodyne interferometer (ref. A.H. Slocum)

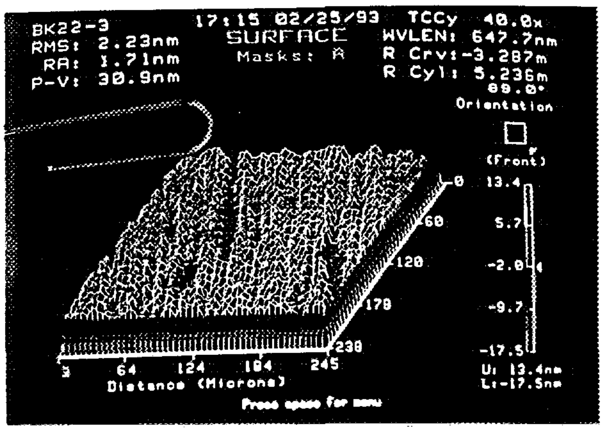


Fig. 18
Interferometric plot of a sub-nanometre surface finish produced on optical germanium.

Fig. 19
Supplied by Prof P. A. McKeown

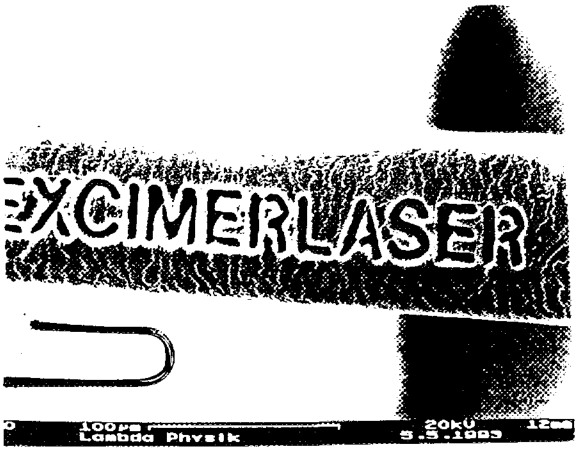


Fig. 20
Human hair micromachined, ~~using an an excimer laser~~. with no discernible damage, by excimer laser mask projection (Courtesy of Exitech Ltd, UK)

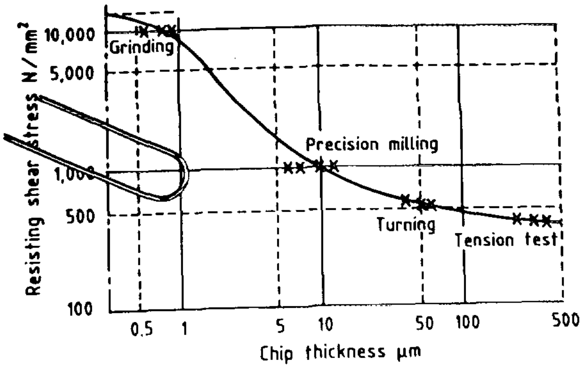
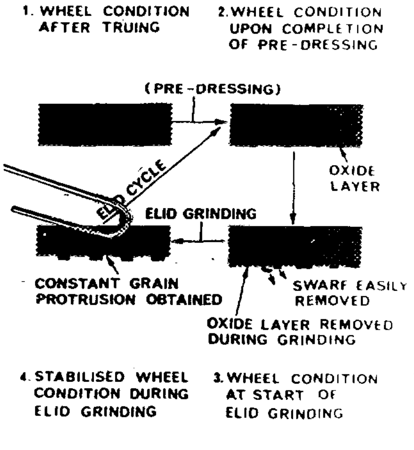


Fig. 21
Resulting shear stress V's chip thickness, showing high stresses with fine machining. (Ref. N. Taniguchi)



(After Ohmori & Nakagawa)

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Fig. 22
The 'Electrolytic In-Process Dressing' (ELID) technique, used for 'ductile mode' grinding.

~~(In photograph 23/6/92)~~

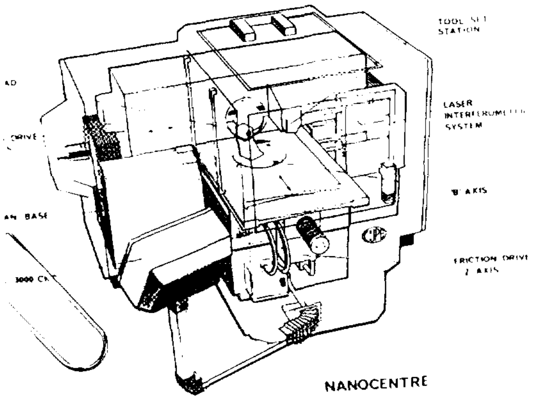

Fig. 23
Nanocentre: for the direct machining of complex aspheric optics, etc. (Courtesy of Cranfield Precision, UK)

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if not get one x 30mm wide
+ one x 160 mm wide → attached
35mm slide

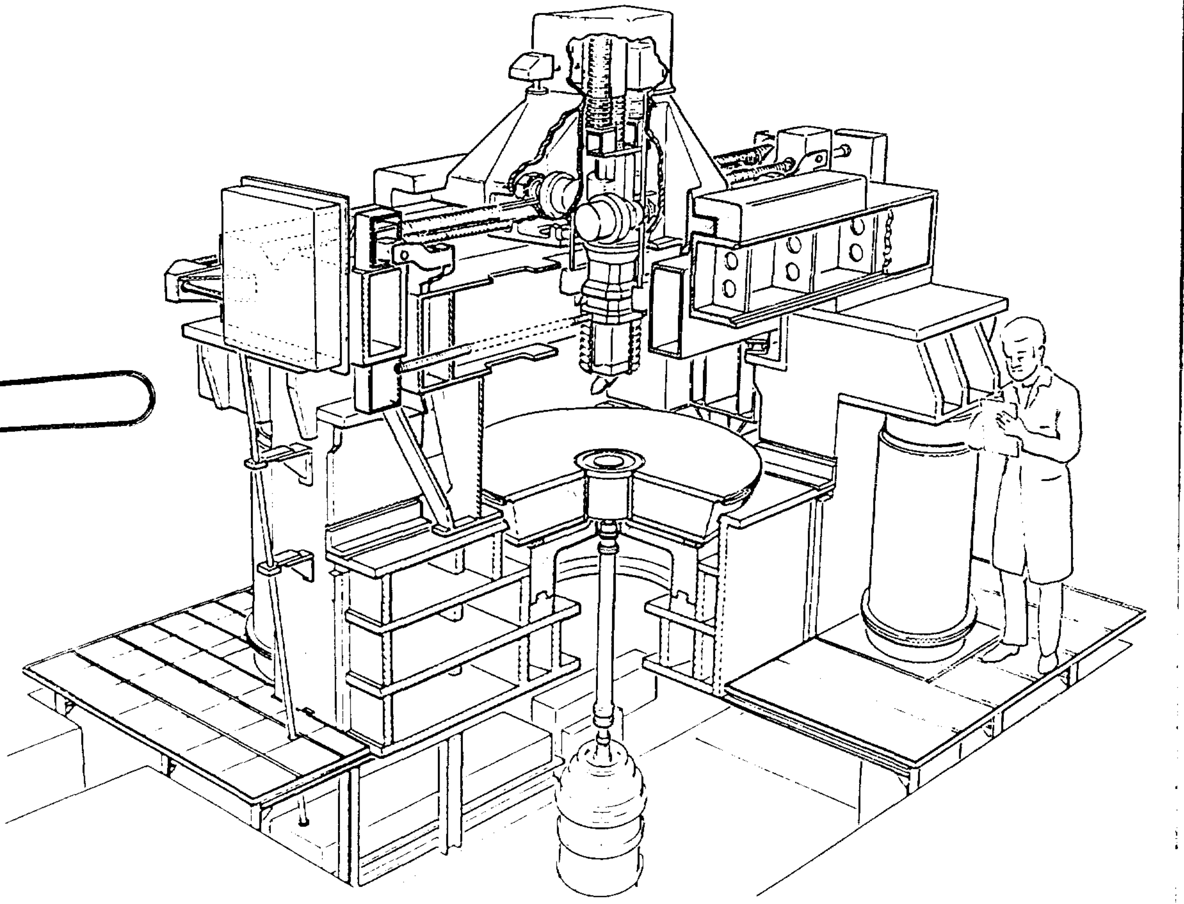

Fig. 24. Large optics diamond turning machine
(Courtesy of Lawrence Livermore National Laboratory, USA)

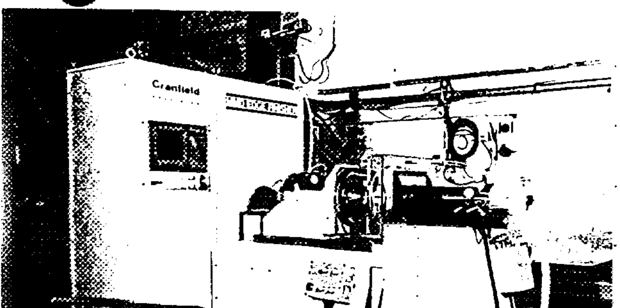

Fig. 25
Computer memory disk edge finishin
machine for alternative disk materia
e.g glass ceramic.
(Courtesy of Cranfield Precision, UK)

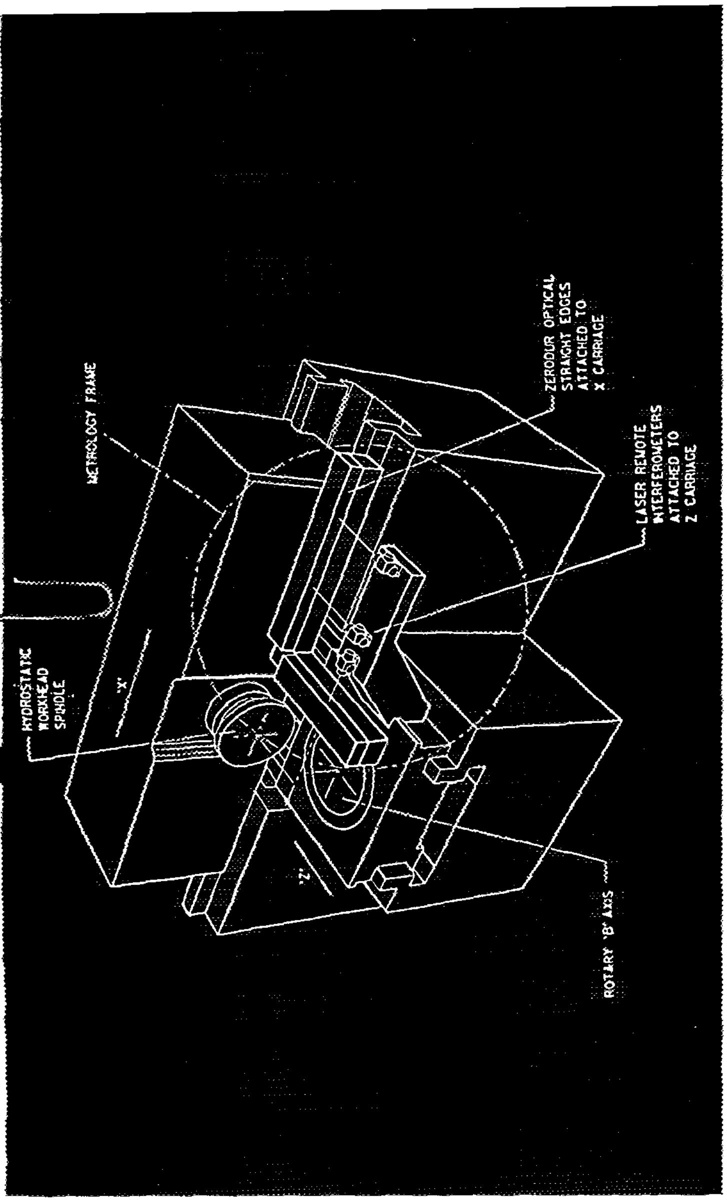

Fig. 26
The use of a metrology frame to improve the geometric accuracy of the Nanocentre, built under the UK's National Initiative on Nanometrolo (NION)

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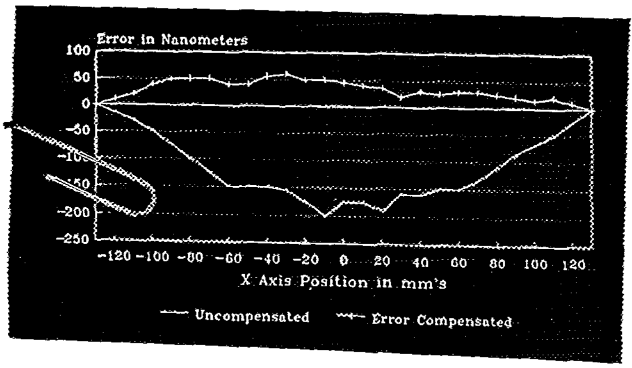

Fig. 27
Nanocentre performance ~~improvements~~ in horizontal straightness error motion obtained with the use of a metrology frame and computer software error compensation techniques

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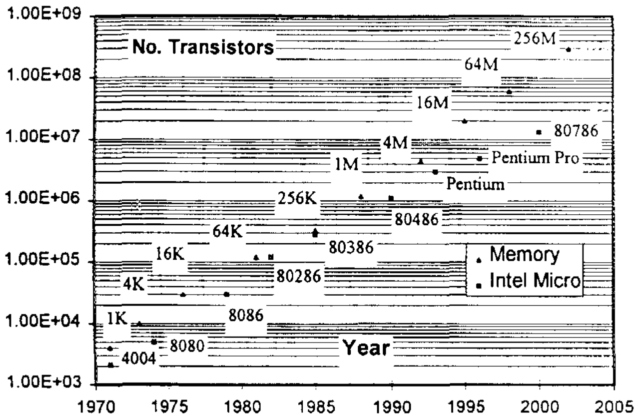
No. Transistors
1.00E+09
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1970
1975
1980
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1990
1995
2000
2005
256M
64M
16M
80786
4M
Pentium Pro
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256K
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Intel Micro

Figure 29

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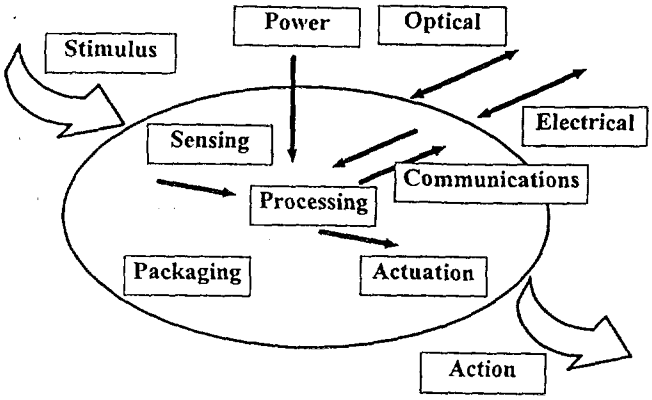


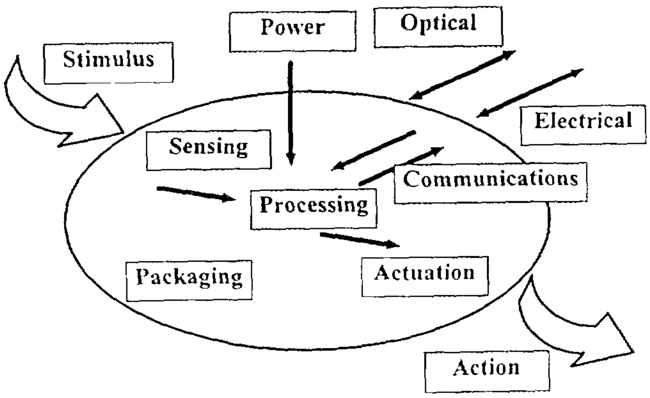


Fig 30

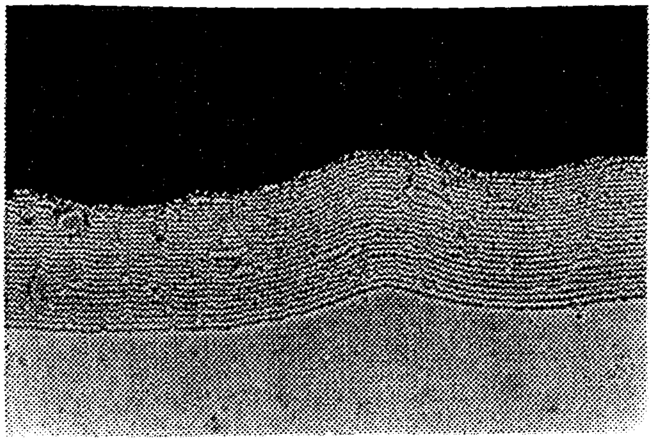


Fig 31a

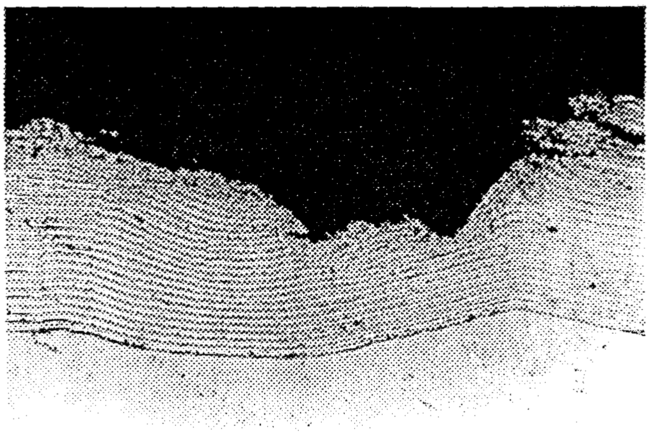


Fig 31b

Fig. 32

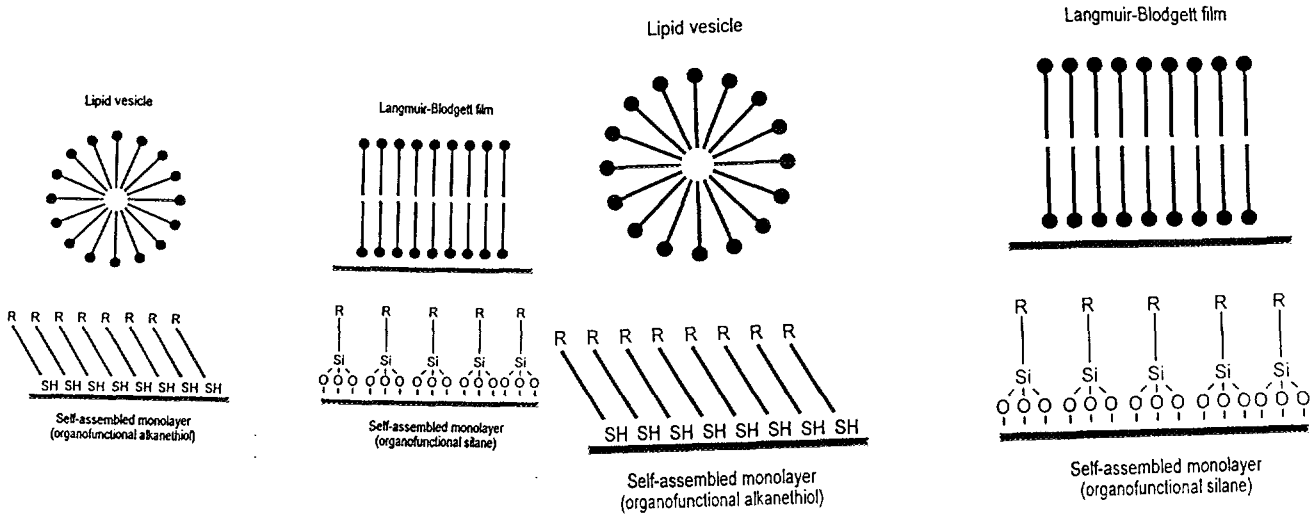
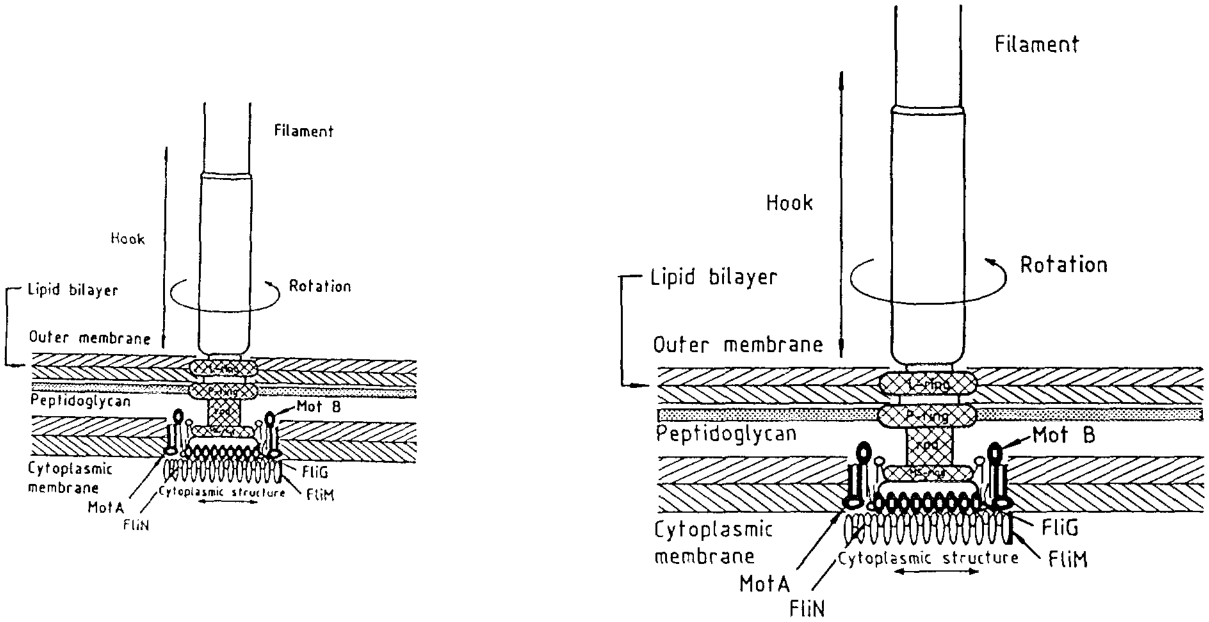

Lipid vesicle
Langmuir-Blodgett film
Lipid vesicle
Langmuir-Blodgett film
R R R R R R R R
SH SH SH SH SH SH SH SH
Self-assembled monolayer
(organofunctional alkanethiol)
R R R R R
Si Si Si Si Si
O O O O O O O O O O O O O O O O
Self-assembled monolayer
(organofunctional silane)
R R R R R R R R
SH SH SH SH SH SH SH SH
Self-assembled monolayer
(organofunctional alkanethiol)
R R R R R
Si Si Si Si Si
O O O O O O O O O O O O O O O O
Self-assembled monolayer
(organofunctional silane)

Fig 33


Filament
Hook
Lipid bilayer
Rotation
Outer membrane
Peptidoglycan
Mot B
Cytoplasmic membrane
MotA
FliN
Cytoplasmic structure
FliG
FliM
Filament
Hook
Lipid bilayer
Rotation
Outer membrane
L-ring
P-ring
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Peptidoglycan
Mot B
Cytoplasmic membrane
MotA
FliN
Cytoplasmic structure
FliG
FliM

Fig 34

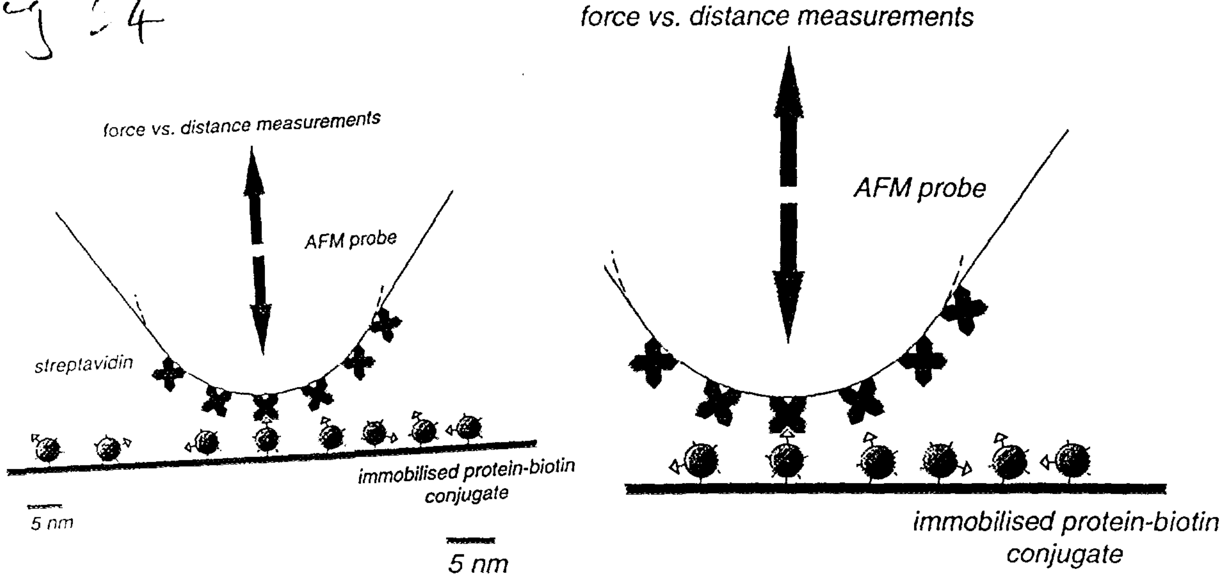
force vs. distance measurements
AFM probe
streptavidin
immobilised protein-biotin conjugate
5 nm
force vs. distance measurements
AFM probe
immobilised protein-biotin conjugate
5 nm

Fig 35

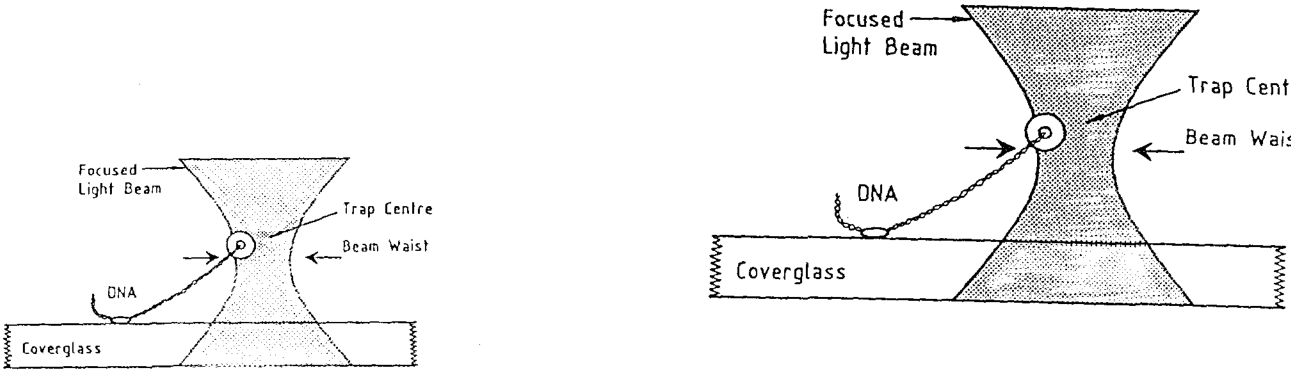
Focused Light Beam
Trap Centre
Beam Waist
DNA
Coverglass
Focused Light Beam
Trap Centre
Beam Waist
DNA
Coverglass

Fig. 36