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Focused high energy proton beam micromachining: A perspective view

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Abstract

Micromachining techniques utilising optical, UV and X-ray photons, as well as electrons, low energy heavy ions and high energy light ions (protons), are briefly reviewed. The advantages and disadvantages of each process are discussed. High energy ion beam micromachining (proton micromachining) is a new process which exhibits a unique feature; direct-write 3-dimensional micromachining at submicron resolutions. Although this technique may not compete with conventional mask processes for producing high volume batch production of microcomponents, high energy ion beam micromachining may have a significant role in rapid prototyping, research into the characteristics of microstructures, and the manufacture of molds, stamps and thick masks. Several examples of high energy proton micromachining are presented to illustrate the potential of the technique. © 1999 Elsevier Science B.V. All rights reserved.

1. Introduction

The miniaturisation of machines, actuators and sensors etc. and the integration of these micromechanical components with electronic devices (microelectromechanical systems – MEMS), is considered to be a new high-technology growth area of enormous potential. The demand for microstructures and MEMS over the next decade is expected to grow in the same way that IC production has grown in the last two decades. This paper briefly reviews selected micromachining techniques capable of producing sub-micron structures, and does not deal with the many techniques (e.g. laser beam and plasma beam machining, electro-discharge wire cutting etc.) which have been very successful in large structure micromachining.

Included in the review of sub-micron techniques is a recently developed promising new technique which utilises a focused nuclear particle beam. In this paper we refer to this new technique as high energy ion beam micromachining, or sometimes the more specific proton micromachining, since most of the early work has been carried out using MeV protons. Since it is important that any new technique offers some advantages compared with other micromachining techniques, we discuss possible niche areas of high energy ion beam micromachining and describe some areas of potential exploitation.

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2. Review of micromachining techniques

The majority of sub-micron machining procedures involve two types of interaction; electromagnetic radiation (e.g. optical, UV or X-ray photons) or charged particles (electrons, low energy heavy ions, high energy light ions). In general the micromachining procedures based on electromagnetic radiation require masks. In mask processes a selective pattern of radiation is transmitted through a structured mask on to a resist material, and subsequent development of the exposed resist using specific chemicals can produce microstructures. The use of a mask has significant advantages in the commercial sector, in that if the mask incorporates multiple repeat patterns then multiple microstructures can be manufactured in one exposure. The production of multiple repeat microstructures, resulting in a reduced price per component, is almost a prerequisite for access to the commercial market.

The use of a mask with charged particles is not so convenient, since in general the greater energy deposited in the mask during exposure results in mask instabilities due to heat expansion, stress and damage. The use of charged particle techniques for micromachining therefore is essentially limited to direct write processes, where a focused charged particle beam is scanned over a material in a specific pattern to produce microstructures. Although the direct-write process has the advantage that masks are not required, it has an obvious limitation in that the production of microcomponents is a serial process which has greatly reduced efficiency for multiple component production.

Micromachining procedures capable of producing sub-micron structures are briefly reviewed below. Included are the mask processes utilising optical, UV and X-ray photons, together with the direct-write procedures which utilise electrons, low energy heavy ions, and high energy light ions. For completeness, a new technique of high potential is also included, that of atomic manipulation. This technique utilises recent advances in probe microscopy. A summary of some characteristics of the techniques described is listed in Table 1. The extensive subject of microfabrication, microlithography and micromachining is covered comprehensively in two excellent recent books by Madou [1] and Rai Choudhury [2].

2.1. Optical lithography [3]

In general, commercial micromachining technology is closely allied to technological innovation in the IC industry, since it is economically sensible to utilise the current huge investments in manpower expertise, high cost capital equipment, and decades of research and development. Currently therefore, commercial silicon micromachining based on optical lithography is the dominant process for micromachining, and many successful integrated devices (e.g. accelerometers, gyroscopes) have been manufactured using this process.

The optical lithography process (photo-lithography) utilises optical light passing through a patterned mask. The transmission of light exposes a specific geometrical pattern in a resist layer laid down on a substrate (usually silicon) and the exposed regions of the resist are subsequently removed using chemicals. If the developed resist layer is sufficiently thin so that the silicon substrate is exposed during the development process, then subsequent chemical etching can result in microstructure formation in the silicon substrate. Although photolithography is essentially a surface micromachining technique and therefore two-dimensional, various wet and dry etching techniques have been successful in producing 3-D microstructures.

It is further predicted that SIO (silicon on insulator) IC technology utilising a SiO_2 buried layer may be a promising candidate for industrial 3-D micromachining in the future. In this process the SiO_2 layer can act both as a stop for silicon etching, or as a sacrificial layer which can be removed in order to produce released structures or moving components.

There is however a fundamental limit placed upon the achievable structure size in optical lithography. Due to the wavelength of light and diffraction effects the construction of structures of sizes below about 250 nm is essentially out of reach.

Table 1
Summary of current techniques for sub-micron micro-machining

Technique	Requires resist exposure	Potential Sub-100 nm capability	Requires mask	Direct write	Facility availability	High volume production capability	3-D capability
Optical lithography	Yes	No	Yes	No	Widespread Use in industry	Yes	No[a]
X-ray lithography (LIGA)	Yes	Yes: Depends on mask	Yes	No	Scarce and expensive	Yes	Yes
UV Lithography	Yes	Yes: Depends on mask	Yes	No	Scarce	Yes	Yes
Electron beam writing	Yes	Yes: Currently achieved	No	Yes	Medium availability	No	No
Low energy ion beam writing (FIB)	No	Yes: Depends on focusing system	No	Yes	Scarce	No	No[b]
High energy ion beam writing	Yes	Yes: Depends on focusing system	No	Yes	Very scarce	No	Yes
Atomic Processing using Probe Microscope	No	Yes: Atomic resolutions	No	Yes	Available and cheap	No	No

[a] Optical lithography is a surface technique. However, new supplementary dry etch methods such as plasma etching are being used to produce submicron 3-D structures from 2-D surface structures in silicon.
[b] Low energy ion beam micro-machining (FIB) relies on sputtering atoms from the surface. 3-D structures can be produced by continuous erosion at the same point, but in practice this process is much too slow for practical 3-D micro-component production.

2.2. X-ray lithography (LIGA) [4]

X-ray lithography potentially has the capability of manufacturing structures with sizes less than 250 nm, due to the shorter wavelengths involved. In addition, because of the penetration properties of X-rays in resists such as PMMA, 3-D structures can be readily manufactured, and high aspect ratios approaching 100 can been achieved. When the developed resist is used in conjunction with electrodeposition, which fills the resist mold with metal, then 3-D metallic microstructures can be produced. This process is now universally known by its German acronym LIGA [X-ray Lithographie, Galvanoformung (electrodeposition), and Abformtechnic (molding)]. The use of LIGA however is limited and is not widely used, because in order to achieve the relatively high level of photon flux suitable for mass production of components, an expensive electron synchrotron accelerator (synchrotron light source) is required. Further, the production of sub 250-nm components is difficult due to the challenges encountered in the manufacture of high resolution masks, which in general have to be sufficiently thick to produce pattern contrast in the transmitted X-rays.

2.3. Deep UV lithography [5]

A compromise between the relatively well understood and ubiquitous photolithography, which is used to manufacture shallow microcomponents of dimensions >250 nm, and the expensive LIGA process, which has the potential to manufacture sub-250 nm 3-D microcomponents, is deep UV lithography. In this new technique, which is still under development, the shorter wavelengths of UV are used to minimise diffraction effects. Special types of resist are used which are transparent to UV, thereby allowing the UV to penetrate deep into the resist for 3-D exposures. The success of the technique however depends on the development of a suitable resist not only with characteristics of transparency to UV light but also with high resist sensitivity to UV. Resist sensitivity can be improved many-fold using chemical amplification, where a single photon initiates a cascade of chemical reactions to increase scissioning (for positive resists), or cross linking (for negative resists). Negative resists such as SU-8 (Shell Chemical) are proving very successful for deep UV lithography, although at the moment the poor stability and swelling of microstructures developed from chemically amplified resists may limit the ultimate structure size. Aspect ratios of 10 can be currently achieved using deep UV lithography [6], which compares favourably with LIGA.

2.4. Electron beam lithography [7]

E-beam lithography capitalises on the success of electron microscope technology, where a keV electron beam can be focused to atomic dimensions. In principle therefore, by writing a highly focused electron beam over a suitable resist material, very fine structures well below 100 nm dimensions can be produced. The main disadvantages of e-beam lithography is that because the electrons are light, they scatter very easily from the electrons in the resist material, and both the scattered and secondary electrons cause lateral spread due to diffusion effects (proximity effects). Consequently the very high spatial resolution of the electron beam achievable at the surface quickly deteriorates as the beam penetrates the resist, and this makes e-beam lithography unsuitable for high resolution 3-D microstructures. The advantage of not requiring a mask to produce high definition surface structures in resist material is counterbalanced by the disadvantage that e-beam direct-writing, like all direct-write processes, is inherently slow compared with mask fabrication processes. E-beam writing has therefore been limited to mask making and direct-writing on wafers for specialist applications.

2.5. Low energy ion beam direct-writing [8]

Ion beam lithography (or focused ion beam (FIB) milling) is the only charged particle process which does not require a resist, since it relies on the momentum transfer of a direct-write, focused heavy ion beam to sputter away surface atoms. Using high brightness liquid metal sources, sub-100 nm, focused heavy ion beams (e.g. gallium) can be obtained and used to good effect in surface micromachining. A focused heavy ion beam has the advantage that its penetration into material is limited to a few atomic layers and that any resulting secondary electrons have low energy and therefore relatively small lateral diffusion. The consequence of very shallow penetration is that the high spatial resolution of the beam at the surface does not deteriorate below the surface, unlike e-beam writing. The disadvantages of FIB is that it is essentially a surface milling technique, and in order to produce 3-D structures requires a considerable period of time. As a micromachining technique, FIB therefore is essentially limited to research applications, although it has been used successfully for milling in IC repair.

Other ways of utilising ions is to use a plasma to sputter the surface of a material, where selective removal of the material can be achieved through a surface mask. When reactive ions are used, the surface milling process can be enhanced by chemical effects. This dry etch technique is being developed as a complementary 3-D extension technique for photo-lithography: The 2-D structures produced in the surface resist by photo-lithography can be extended deep into the substrate using reactive plasma etching [9].

2.6. High energy ion beam direct writing

Surprisingly, focused high energy ion beam micromachining is the newest of the micromachining techniques. It has been known for many years that individual fast ions in resist material can produce visually identifiable tracks (a procedure used for particle detection and identification). Although surface patterning has been demonstrated using ^{16}O ions [10] and preliminary work on dose exposure carried out using focused protons in PMMA [11], it is only recently that direct write focused ions beams have been used for structural micromachining [12–17]. The high energy micromachining technique, which utilises a scanning focused MeV ion beam to expose resist material, has great potential for producing high aspect ratio 3-D microstructures particularly when protons are used. Submicron structures and aspect ratios approaching 100 have been achieved [13] which compares very favourably with LIGA. The relative merits and disadvantages of high energy ion micromachining are discussed in more detail in Section 3.

2.7. Atomic processing using atom probe microscopy [18,19]

The scanning tunneling microscope is an instrument based on the movement of a sharp tip over a surface. For very small separations, the current induced between the tip and the surface is controlled by quantum mechanical tunneling, and the current exhibits an exponential dependence on the tip/surface distance. Maintaining a constant probe current by keeping the probe/surface distance constant enables surface atoms to be imaged with great effect. The electric fields generated around the probe tip (around 10 V/nm), can be sufficient to displace atoms from their sites and move them over surfaces. If this manipulation is carried out in a controlled manner the technique can be used either to position atoms in particular patterns on a surface, or alternatively produce shallow structures of atomic dimensions.

This type of micromachining (atomic micromanipulation or atomic processing) is by its very nature extremely slow, even when generating simple features. Nevertheless, although atomic processing is still in its infancy, the technique is being developed by many groups worldwide as a consequence of its extremely high potential as well as its relative low cost.

3. Advantages and disadvantages of high energy ion beam micromachining

In general the path of a high energy ion (e.g. 2 MeV proton) in matter is largely determined by electronic collisions, with a smaller contribution from forward elastic nuclear scattering. As the average energy transfer per electron collision is relatively low (due to the large mass difference between the ion and the electron), then many thousands of collisions occur and the ion path can be statistically predicted (e.g. using the computer code TRIM) [20]. The ion path can be characterised by three important features:

(a) The degree of scattering per collision is small: The ion in general does not suffer large angle collisions and travels in an approximate straight line as it passes into the sample. The exposure rate with depth is also relatively uniform (except at the end of range).

(b) The ion penetrates the surface of the specimen and travels through many atomic layers before it comes to rest. The range is therefore relatively high, particularly for high energy light ions such as protons; e.g. 2 MeV protons will penetrate 62 μm into PMMA. An added advantage is that due to the lack of large angle scattering, a focused proton beam will effectively maintain its spatial resolution as it penetrates material (except at the end of range). This is particularly true for thin resists, e.g. a 2 MeV proton beam travelling through a PMMA film of 5 μm will experience less than a 20 nm spread in the beam profile.

(c) Due to the statistical nature of the collision process, the degree of range straggling is small and can be as little as a few percent e.g. the range straggling of 2 MeV protons (range 47 μm) in silicon is approximately 1.6 μm. Ions of the same incident energy therefore travel through material and stop at approximately the same depth in the sample.

The advantages of using a high energy ion beam for micromachining can be summarised as follows: (a) The focused beam can be directly scanned across the resist, thereby eliminating the need for a mask. (b) The ion beam has a well defined range in resist (unlike X-rays), and therefore the construction of slots, channels, holes, etc. has a well defined depth. (c) The use of ion beams of different energies enables slots, channels and holes to be manufactured with different specific depths. (d) By changing the angle of the resist with respect to the beam, complex non-prismatic shapes can be machined. (e) The technology now exists for producing proton microbeam spot sizes at the 100 nm level [21].

The disadvantages of the technique, as is the case with all direct write technologies, is that in general the process is too slow for commercial direct high volume batch production of micro-components.

Fig. 1(a–f) show the type of structures that can currently be produced using proton micromachining, and indicates that microstructures of good quality with precisely controlled depth properties can be manufactured [13,15]. The structures were manufactured using the micromachining facility at the Research Centre for Nuclear Microscopy, National University of Singapore. The walls of the structures are in general smooth

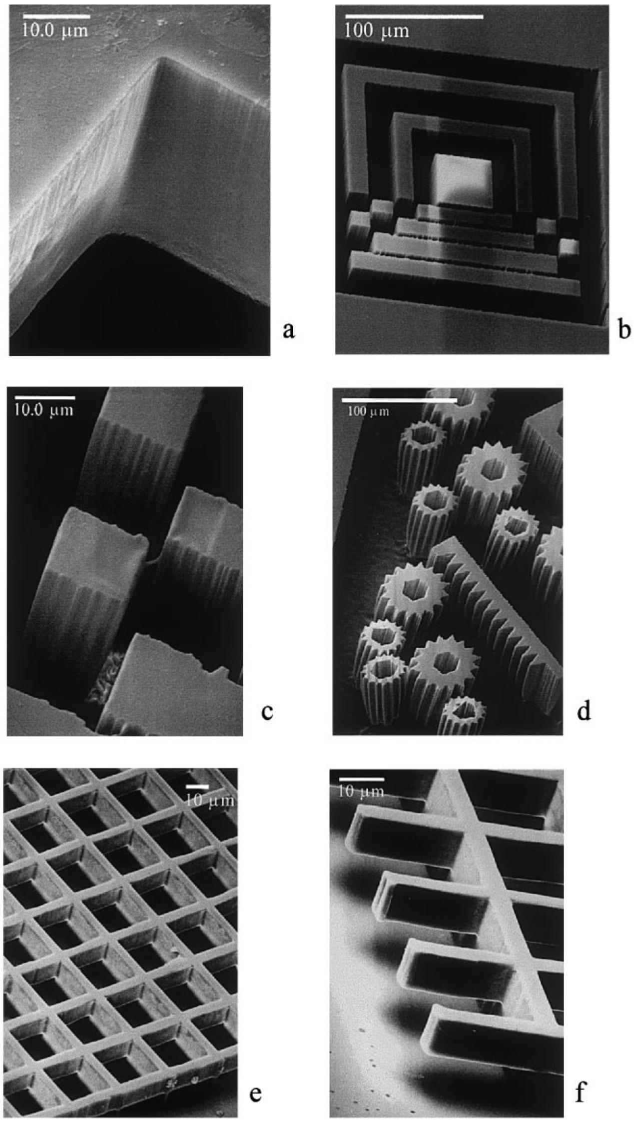

Fig. 1. Electron micrographs of selected microstructures machined using the proton micro-machining facility at the Research Centre for Nuclear Microscopy, National University of Singapore. (a) Structure in PMMA showing a sharp corner and smooth walls, (b) deep patterns in PMMA, (c) higher magnification micrograph of pillars in (b) showing ripples in the walls due to beam intensity fluctuations, (d) selection of cogs and gear trains machined from PMMA, showing undercutting at the end of range, (e) suspended grid machined from the negative resist SU-8, using 600 keV and 2 MeV protons and (f) cantilever array, machined from SU-8, using 600 keV and 2 MeV protons.

and straight (Fig. 1(a)), with inside corners defined by the beam resolution. The pillar shown in Fig. 1(c) exhibits ripples in the walls caused by beam intensity fluctuations from the nuclear accelerator: The beam intensity fluctuations are a result of an unstable accelerator and indicate that good energy stabilisation is a prime factor in producing smooth structures. The cogs shown in Fig. 1(d) show undercutting at their bases due to end of range broadening effects: End of range effects can be avoided by using thin resist layers laid down on a flat substrate, so that the beam passes directly through the resist into the substrate [15,16]. Fig. 1(e) and (f) demonstrate the type of structures that can be produced using SU-8 negative resist. Here we have used protons of two different energies (2 MeV and 600 keV) to machine complex shapes such as supported structures, buried cavities, tunnels and cantilevers. This, we believe, represents the first ever demonstration of multiple level machining using only one resist layer.

4. Proton micromachining: niche areas

High energy ion micromachining (e.g. MeV proton micromachining) is the only technique capable of direct-write 3-D micromachining. In order to capitalise on this unique property, it is important that we exploit those features that offer significant advantages compared with other micromachining techniques. As the field becomes more active and widespread then more niche areas will become apparent. To start the ball rolling, however, we have identified several areas which we believe are areas of high potential.

(a) *Basic Research*: There is a growing need to investigate the properties of microstructures: e.g. fluid flow properties in microchannels, friction properties, wear characteristics of moving parts, inertial properties of cantilevers, bio-activity of microimplants etc. For basic research purposes high volume production is not necessary, and direct-write production of small numbers of custom-built structures may prove highly advantageous.

(b) *Rapid and cheap prototyping of 3-D microstructures*: With the rapid expansion in batch production of microcomponents, which invariably involves high capital equipment expenditure, there is a need for the rapid and efficient development of working prototypes. Again, there is no need for batch manufacture, since the emphasis is then on product development rather than mass production, and it is in this area that direct-write processes may have both cost and time advantages.

(c) *Stamp and mold manufacture*: It is unlikely that proton micromachining, or any other direct-write process, will make great inroads into the high volume commercial market except perhaps in the specialist field. However, proton micromachining does have the potential to manufacture individual 3-D stamps or molds, which can then be used repeatedly for batch and high volume production. Current projects at the Research Centre for Nuclear Microscopy, NUS, include development of 3-D substrates for tissue engineering [17], precision molds for IC packaging, and microchannels for advanced electrophoresis applications.

(d) *Mask production*: X-ray lithography is one process which has the potential to manufacture sub-250 nm components for the IC industry. The technique however requires advanced mask technology: A typical X-ray mask needs to be extremely stable, have sub-250 nm pattern dimensions, and have characteristics such that the pattern is thick enough to block out X-rays which are not required. The mask therefore has to exhibit high aspect ratio structures. Proton micromachining has the potential to manufacture such masks.

5. Conclusion

High energy light ions (e.g. 2 MeV protons) have a well defined penetration depth in matter, with small lateral spread (except at the end of range). High energy ion beam micromachining using a direct-write scanning MeV ion beam is therefore capable of producing 3-D microstructures and components with well defined lateral and depth geometry. The technique is currently able to produce microstructures with high aspect ratios approaching 100 [13], with potential lateral resolutions down to 100 nm, representing the current state-of-the-art performance for 2 MeV proton beams [21]. The technique has high potential in the manufacture of 3-D molds, stamps, and masks for LIGA, and also in the rapid prototyping of microcomponents either for research purposes or for component testing prior to batch production.

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