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Application of Focused Ion Beam Micromachining: A Review

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Abstract. Fabrication of micro and nanoscale components are in high demand for various applications in diversified fields that include automotive, electronics, communication and medicine. Focused ion beam (FIB) machining is one of the techniques for microfabrication of micro devices. This paper presents a review of FIB machining technology that include its parameter, responses, its important component systems, as well as the fundamentals of imaging, milling (etching) and deposition techniques. The application of FIB in micromachining is also presented.

Introduction

In modern technology, the FIB is an extremely vital tool for semiconductor device manufacturing, failure analysis, cross-sectioning of devices, maskless implantation and ion beam assisted etching [1]. FIB sputtering is also used for machining of materials at micro- or nano-scales [1, 2]. The technology has proven to be useful in fabricating microtools applications. In comparison to traditional techniques such as X-ray lithography or UV lithography which are intermediate operations used primarily in creating micro- to nano-scale features on silicon substrates, FIB high resolution technique is able to write directly on any conductive substrates [2, 3]. This paper presents an overview of the FIB system, fundamentals and applications.

Focused Ion Beam System

FIB system. The ion beam is generated from a liquid-metal ion source (LMIS) such as Ga^+ by the application of a strong electric field. Ga^+ has advantages compared to other LMIS metal because of its low temperature melting point (30°C), low volatility, and low vapour pressure. Low melting temperature facilitates the ease of design and operation of the ion source system component. Furthermore, Ga^+ does not chemically react with the tungsten needle component, and its evaporation is negligible [1, 3, 4]. A system of vacuum pump is used to maintain the vacuum inside the column and the work chamber. The ion column is provided with ion pumps. The gas containers are connected to a nozzle assembly inside the vacuum chambers for faster and more selective etching, and for the deposition of materials [5].

Influence of FIB Parameter. The acceleration voltage directs the Ga^+ ions acceleration down to the ion column. This matter determines the speed of the ions or beam energy that is focused towards the substrate. The secondary electron yield of the electron beam can be enlarged by lowering the accelerating voltage. However, in general, for model accelerating voltages at a given beam current, the electron beam deposition is ~10 times slower than the ion beam when depositing platinum [6]. High applied accelerating voltage can sputter a certain depth faster but may cause damage to the substrate surface [7]. Dwell time, duration of time the ion beam remains fixed at one pixel point [8]. Higher aspect ratio of micro holes can be achieved by increasing the dwell time. When the dwell time increases, the bottom surface roughness, R_a will also increase for silicon mold fabrication .As the beam dwell time is reduced, the ion dose of a single scan at each pixel on the pattern is reduced [7]. Additionally, ion dose shows the amount of ion exerted on to the surface of a substrate. A linear relationship is typically observed between the ion dose and the resulting milled depth [7]. Aperture size on the other hand, controls the shape of the Gaussian beam on the substrate. A smaller aperture size produces micro components with good geometrical shape. The aperture allows only the central high intensity core of the beam to go through. Hence the aperture size had a proportional effect on the spot size. The aperture size affects milling time as well as the surface finish [9].

Responses of FIB. Taper angle is exhibited during FIB sputtering of microfeatures that requires depth or height such as microholes. The trend of the Gaussian profile and redeposition effect was found to be the cause of this taper angle existence [6, 10]. This phenomenon shows that the actual geometry shape for microholes may deviate from the desire shape [6]. Longer dwell times increases the taper angle by increasing the ion redeposition effect [11]. In FIB micromachining the aspect ratio is imperfect due to the redeposition of sputtered material on the surfaces of the structures [12]. This may be improved by selecting the substrate material with high sputter yield. Beam current is another factor that limits the achievable aspect ratio but it is difficult to obtain a general relationship between the beam current and the aspect ratio since it is different for different substrates [13]. R_a was found to be the most crucial factor in producing good surface quality of micrcomponents [14, 15, 16]. Researchers have found that the sidewall R_a is estimated to be below 100 nm when sputtering GaN by using a lower beam current since a large beam diameter is produced when a high beam current is used [10, 14]. Material removal rate, MRR in physical sputtering depends on parameters such as dwell time. There was research done on exploring the abnormally high MRR issues during ultra-rapid FIB direct patterning of PMMA. The MRR is in fact controlled by the distance from the sample surface. Strong surface enhancement has been observed in PMMA sputtering and MRR decreases with the total exposure time [17].

FIB Imaging, Milling, and Deposition

Imaging. Imaging is achieved when the fine ion beam is raster scanned over a substrate. High-spatial-resolution images can be obtained from the secondary electrons [2, 3, 4]. In crystalline materials like aluminium and copper, the ion penetration depth varies due to channelling along open in the lattice structure. The depth of the penetration of the channelled incident ion varies with the relative angle between the ion beam and the lattice plane and the interplanar spacing of the lattice [5]. Since the secondary electron emission rate depends on the penetration depth, FIB can be used to image crystal grains, revealing different crystal orientations [3].

Milling. The removal of sample material is achieved using a high ion current beam. By scanning the beam over the substrate, an arbitrary shape can be etched, whereby physical sputtering of the sample material occurs [5]. The milling process speed can be increased by using an etching gas Xenon difluoride (XeF_2) into the work chamber during milling. It will increase the etching rate and the selectivity towards different materials by chemically facilitating the removal of reaction products. The technique is called gas-assisted etching (GAE) [1, 3, 18].

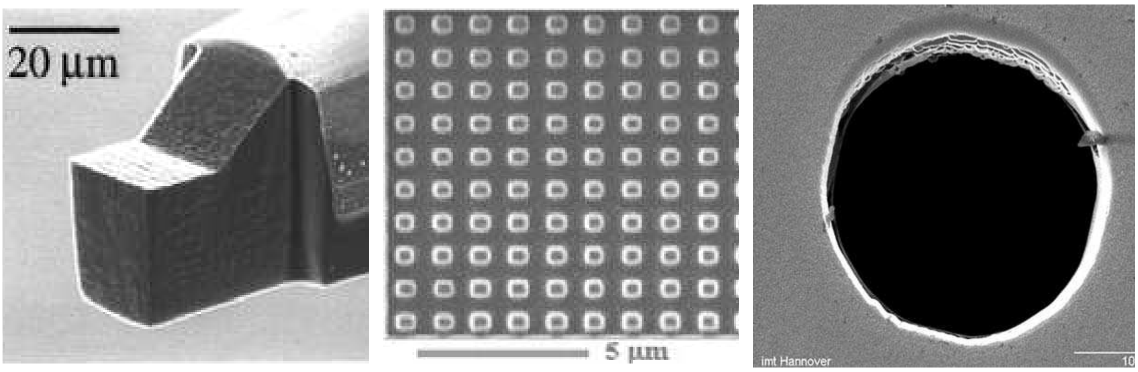
Deposition. FIB allows the localized maskless deposition of metal and insulator materials known as chemical vapour deposition (CVD). The main difference is better resolution, but lower deposition rate of FIB. The deposited material is not fully pure because organic contaminations and Ga^+ ions are inevitably included [5]. The smallest features that can be deposited are of the order of 100 nm (lateral dimension). The minimum thickness is about 10 nm [3].

Applications

Fabrication of Microtools. The development of cutting tools like the diamond cutting tool for micro- lathes and mills can be done using FIB. The dimensions of micro cutting within the range of 15-100 µm can easily be manufactured using FIB sputtering [18]. Fig. 1(a) shows the high magnification scanning electron micrograph of the same diamond tool in perspective view to show the fabricated cutting edge and other facets [2]. Complex geometric features like tool nose radius, rake angles, and relief angles are controlled in nm range. Variety of tool geometries are produced with the help of FIB sputtering technique on the tool materials such as tungsten carbide, high-speed tool steel, and single crystal diamond. Among the three of the tool types, diamond requires significantly longer machining time due to higher C-C surface bonding energy. Steel and carbide require smaller time for shaping using the FIB fabrication process. Previous research shows that a 25 µm wide threading tool made up using steel or carbide can be fabricated in 3-5 hours with a 2nA ion beam [1, 18].

FIB Nanofabrication. FIB can be used to fabricate sub-5 nm feature sizes. This is a size that is difficult to produce using standard fabrication processes. There are methods involved to mill through thin membranes (30-200 nm). The first method is used by milling through the membrane to make a hole otherwise done by electron or ion beam SiO_2-assisted deposition which is used to fill the hole and reduce its diameter. The result of SiO_2 ring was used to attach DNA around the pores for biosensing. The other method is to make sub-5 nm diameter nanopores that involve milling through the membranes and use of redeposition to produce a cone shaped hole. Si_3N_4 membranes are usually used as well as the SiC membranes. The SiC membranes were coated with metallic thin film to balance the intrinsic stress surrounded by the membranes [19]. Fig. 1(b) shows the arrays of 500 nm x 500 nm sized square nanopillars on single crystal silicon.

High Aspect Ratio Microstructures. When fabricating thin-films with high aspect ratio for micro devices, a low stress level is preferable since excessive stress may cause in a delamination. The hole drilling method is used in order to measure the internal stress [20, 21]. A circular hole is grilled in the structure under tension to a depth equal to the hole diameter. The hole changes its diameter due to its tensile stress and compressive stress. FIB is used to do the hole in range of a few microns up to several ten microns into thin-films. The electroplating process carried using high current densities which causes a high deposition rate and internal stress [20]. Fig. 1(c) shows the micro hole etched through NiFe thin-flim with compressive stress using SEM.



(a) (b) (c)

Fig. 1(a): High magnification scanning electron micrograph of same diamond tool [1], (b): Arrays of 500 nm x 500 nm sized square nanopillars on single crystal silicon [21], (c): SEM micrograph of a micro hole etched through the NiFe thin-film [20].

Conclusions

- FIB plays a significant role in microtechnology especially in semiconductors and microsystem technology.
- The main advantage of the FIB over other lithography techniques is the capability of direct writing on the specimen and the ability to machine virtually any material with any geometry in short overall design time.
- This review presented the overview of the FIB system, fundamentals and applications FIB can act as a microtool fabrication for microlathe machine, FIB nanofabrication and high aspect ratio microstructures.

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