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Rapid communication

High speed micro-fabrication using inductively coupled plasma ion source based focused ion beam system

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ABSTRACT

A compact inductively coupled plasma ion source based focused ion beam system (ICP-FIB), capable of producing intense FIB of gaseous elements is developed. Ar and Xe ion beams of 20–4700 nA are focused to spot sizes in the range of 2–30 μm. Experiments using Ar and Xe ion beams of a few microamperes showed milling speeds that are 25–150 times higher than that of a conventional FIB. Milling of micro-apertures in less than 100 s through 100 μm thick Ta and Mo foils and in less than 10 s through 12 μm gold and 25 μm aluminum foils is demonstrated. In this article, the potential of ICP-FIB in high speed milling of micro apertures and large scale micro patterns are presented. Also the possibility of high speed synthesis of nano-pores with tunable pore sizes is discussed.

Due to the advent of large number of microdevices in various advanced technological fields, FIB technology has found its place in the realms beyond the conventional applications. Besides synthesis of nanoscale structures/patterns, conventional FIB systems are very often being used to synthesize micro and macro patterns where volumes of several million μm^3 are to be milled [1–4]. However, conventional FIB systems based on liquid metal ion source (LMIS-FIB) would take prohibitively long time to mill large volumes due to availability of only a few nA current. The best reported milling rate of LMIS-FIB is not more than 5–10 $\mu m^3/s$ on most of the materials and due to this low throughput, it is mostly restricted to the applications of high cost. In addition, the LMIS-FIB causes contamination by metallic ions on the milled surfaces. However, till today, LMIS-FIB is the best system for milling in nanoscales. In order to overcome the limitations of low throughput and contamination, authors developed ICP-FIB which is capable of focusing three order larger currents of ion beams of inert gases into spot size of few micrometers [5]. Efforts are underway to further reduce the spot size to submicron sizes. Smith et al. have demonstrated submicron size beams of 30 keV energy from similar system [6]. The authors have demonstrated focusing of 10 keV Xe ion beams with currents 1 μA and 2 μA into 4 μm and 7.5 μm respectively, while similar currents of 30 keV Ga ions, if available from LMIS, cannot be focused to sizes less than 200 μm spot size. The high current capability of ICP-FIB is due to high angular current density (J_Ω) of the ion beam extracted from ICP ion source. Experiments have shown that the ICP ion source is capable of producing ion beam of various gaseous elements with J_Ω of three orders higher than that of various ion beams from LMIS [7]. Since milling rates are directly proportional to the available ion current in the focused spot, this newly developed ICP-FIB has superior performance in FIB applications that are beyond the capability of LMIS-FIB systems such as rapid milling of large volumes of material without contaminating the milled surfaces. In addition, the ICP-FIB has advantage of focusing ions of all the gaseous elements and in particular xenon ions which are inert and twice heavier than gallium ions. Comparison of the performances of Ga LMIS-FIB and Xe ICP-FIB with same energy of ions (30 keV), it can be shown that the milling rates of ICP-FIB can be at least 50 times higher due to availability of higher current. Fabrication of devices such as micron size SAW devices [8], micro electrodes for plasma generation [9], nano and micro groves, micropillars [10], microfluidic channels [11] [12], micro molds/micro replication tools [13], micro-coils for magnetic actuators [14], microsize plasma chips [15], mechanical micro-tools [3,2,16], beams, cantilevers, nozzles, vacuum microelectronics devices, fine leakage controls in vacuum technology etc need removal of large volume and currently they are being fabricated using conventional microfabrication techniques. The high milling rates of the newly developed ICP-FIB enables it to be used in rapid fabrication of the some of the above devices by direct-write method and some of

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them by eliminating several steps followed in conventional processes.

In this article, a set of experiments are presented to evaluate the milling rates and throughput of ICP-FIB on Si, Al, Au, Cu which are commonly used in micro-devices and Ta, Mo and WC which are hard and high temperature materials. Experiments to demonstrate the high throughput capability of ICP-FIB in fabrication of micro-apertures and large scale micro-patterns are also presented. To the best of our knowledge the milling rates of materials by gaseous ion beams from ICP-FIB system have not been reported so far.

The ICP-FIB system and characteristics of the ion source which is used to carry out the experiments in this article are presented in publications by the authors [5,7,17,18]. A two lens focusing column is employed to focus the beam at a working distance of about 2 mm. Ion beams of various gases, in the range of 20–4700 nA could be focused to spot sizes in the range of 2–30 μm and current density as high as 4.5 A/cm^2 could be achieved for certain range of spot sizes. Specimen to be milled and beam profile measurement instrumentation are installed downstream of the last lens at 2 mm working distance. Further downstream, a secondary electron suppressed Faraday cup is installed to measure the beam current.

Each sample to be milled was cut into small flat piece of area of a few square centimeters assembled on a ring shaped sample holder which inturn is placed on translation stage. Ring shaped sample holder facilitates transmission of ion beam through the aperture milled in the sample by focused ion beam and gets registered onto the Faraday cup. An application written in LabView measures the time taken to create an aperture i. e, the elapsed time from the time of incidence of the beam on the sample to the time of first registration of smallest measurable current on Faraday cup. A realtime graph of Faraday cup current with time is plotted with the sampling rate of one data per second. Initial experiments were carried out using argon ion beam focused onto 60 μm thick free standing copper foil. Fig. 1 shows the milling characteristics of 60 μm thick copper by argon and xenon ion beams of different intensity and energy. The solid line in the figure shows the milling characteristics by 500 nA, 7 keV argon ion beam of 12 μm diameter. As shown in this graph until about 105 s, the Faraday cup does not register any current since all the ions are blocked by the sample. Once the aperture is formed, ion start passing through the aperture. Initially the rate of rise of current read by Faraday cup is higher and then it saturates with time. The saturated total current measured by Faraday cup is always found to be less than the total beam current incident on the specimen since the ions that are out of focus are blocked by the sample. Even after 500 s, there is a steady but slow rise in the Faraday cup current due to the milling by ions in the tail region of the distribution. Ion beam density distribution is measured and found to be Gaussian and hence the milling speed is significantly higher at the region on the sample with peak of the distribution and least at the tail of the distribution. In all the experiments with thinner samples, it is observed that the milling characteristics reflects the shape of the beam. The same experiment is carried out on same sample by using 2000 nA, 10 keV xenon ion beam of 12 μm diameter. Xenon being 3.27 times heavier, has 2.05 times higher sputtering yield (ratio of yield of 10 keV Xe and 7 keV Ar) than that of argon. The milling characteristics of xenon ion beam is shown in Fig. 1 by dotted line where the aperture is milled in just 16 s which is significantly faster than that milled by 7 keV, 500 nA argon beam. Once the aperture is made, in the initial phase there is a rapid rise in the current on the Faraday cup (50 nA/s) indicating rapid widening of the aperture. Within 20 s after the initial opening of the aperture, 50% of the incident current i. e, 1000 nA was transmitted through the aperture (which is not shown in the figure). A continous array of apertures were milled by blanking the beam and advancing the sample by small distance soon after detecting small current passing through the milled aperture. Within about 170 s 10 through-holes were drilled which is a significantly high speed and not reported so far. The experiments under same conditions on 12 μm thick aluminum foil shows the milling times less than 2 s and could be sliced continuously at a rate of about 8–10 μm/s.

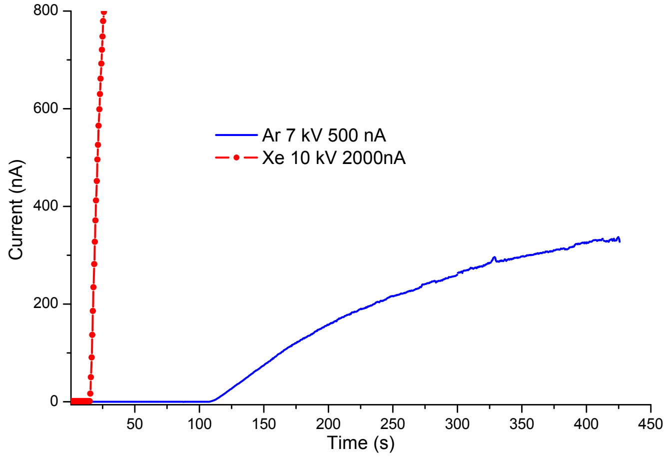

Fig. 1. Milling characteristics of 7 keV, 500 nA Ar and 10 keV, 1000 nA Xe ion beam on 60 μm thick Cu.

Fig. 2 shows the scanning electron microscope images of apertures milled by 7 keV, 500 nA argon ion beam of 12 μm diameter. Fig. 2A shows the milled aperture where the milling was stopped after detecting about 50 nA of current on the Faraday cup, which resulted in the fabrication of an aperture of less than 2 μm width although the beam size is 12 μm. By stopping the milling after detecting a few pA, even nanometer size apertures can be accurately synthesized. However, since the milling takes place at extremely high speed, and there are associated delays with the electronics, power supplies etc, it is difficult to instantly stop the milling process soon after detecting the current. In order to mill nano apertures and with controlled dimensions it is essential to monitor the transmitted current with high speed and stop the milling process at a predetermined current. Since the current passing through the aperture is proportional to the area of aperture for a given shape of the beam, by terminating the milling process at predefined transmitted current, the size of the milled aperture can be very accurately controlled. In the experiments presented in this article, the shape of the opening of an aperture is not circular due to rough surface of the foil and polycrystalline nature of the material or it could be due to some contamination on the rear side of the foil. The apertures do not have vertical walls since the ion beam profile is Gaussian and has significant current in the tail of the distribution and they replicate the Guassian shape of the beam. The round edges are also partly due to the redeposition of the sputtered particles from deeper section of the foil. Fig. 2B shows the aperture milled for 350 s through which about 300 nA current is transmitted. Aperture size is 25 μm which is wider than the beam diameter due to sputtering by ions in the tail region of the distribution. Similar milling experiments were carried out on much thicker material that have very low sputtering yield such as tantalum, molybdenum and tungsten carbide. Fig. 3 shows a typical milling characteristics of 100 μm thick tantalum sheet by 10 keV, 1000 nA and 2000 nA of Xe ion beam of 14 μm and 12 μm diameter respectively. Ratio of the current density on the sample (1.76/0.65) and the ratio of time taken to mill through-holes (340/120) are almost same indicating that the milling rate can be increased by a same factor as the ratio of the current density at the same energy. Since the aspect ratio is high in thicker samples, the redeposition effect become