DEVELOPMENT OF PLASMA ION SOURCE BASED MICROMACHINING SYSTEM

Nabhiraj P Y
Variable Energy Cyclotron Centre, Kolkata

Abstract

A compact high performance Inductively Coupled Plasma based (ICP) RF ion source operating at 13.56 MHz frequency is developed for production of low energy beams with micron size dimensions for high speed micromachining applications. To produce fine beams with high current density, ion source must produce high current ion beams with low energy spread and low divergence. Systematic characterizations have been carried out on the ion source and the extracted ion beams. The plasma source has exhibited a reduced brightness of $1x10^5$ A/m^2-sr-eV and ion energy spread of less than 5eV. The angular current intensity of this source is >10 mA/Sr which is about three order higher than the traditional Liquid Metal Ion Source (LMIS). Ions are extracted by two electrode extraction system with 1 mm aperture and accelerated up to 8 KeV. Initial tests with the two lens focusing column, about 20 nA beam could be focused in 1.5 µm spot at working distance of 1 mm. The ion source life time and the stability has been excellent. Several experiments have been carried out to estimate the capability of this system for high micromachining applications. Various types of micro patterns have been created on Si wafer with Ar ion beam. Milling rate of > 1 µm^3 are easily possible with this system. It is expected that with few more modifications in ion source as well as focusing column, milling rates of one order more and focused spot size of submicron dimensions can easily be achieved.

INTRODUCTION

Focused ion beams (FIB) are proved to be the preferred tools over laser milling for cutting conductors in microchips, producing micron size holes in metals, mill the micron size mechanical tools and are conventional tools for secondary ion mass spectrometry (SIMS) [1]. Mostly the FIB systems are developed utilizing Liquid Metal Ion sources (LMIS). However, these sources suffer from serious disadvantage of producing only a few metallic ion beams. Duoplasmatron is another ion source being developed to produce the micron size beams but it has lower brightness and has a short operating life span. Inductively coupled plasma based (ICP) RF ion source is another promising one for FIB applications due to the fact that it has good ionization efficiency and is capable of producing ion beams of various gaseous and metallic elements. In addition, ICP RF ion source, being filamentless, it also can produce ion beam of corrosive gases. Significant works are being carried out to perfect the technology of using RF ion sources to produce focused ion beam. Considering the ease of operation and the simplicity in the construction, a low energy FIB system for micro patterning applications has been developed. It consists of a high brightness ICP ion source and a focusing column with a two Einzel lenses. In this article we describe the ion source, design of focusing column, characterization of ion beam and few examples of micromachining on the silicon wafer.

MODIFICATIONS IN THE ION SOURCE

The 13.45 MHz ICP ion source, described by Nabhiraj et.al [2] is modified for enhancing the performance. To initiate the plasma and obtain higher ion currents at lower powers, plasma chamber was modified by dividing it into two portions by a quartz separator with small aperture for gas flow. Helical RF antenna is wound only on the lower plasma chamber and a 30% transparent Faraday shield with same height as the antenna is interposed between the quartz tube and the antenna as shown in Fig. 1. With the decrease in the volume, the power density is almost doubled to approximately 4 W/cm^3. At low RF powers, RF voltages from the high voltage end of the antenna cause capacitive discharge in the upper plasma chamber as shown in figure 1A and electrons from this discharge diffuse into the lower chamber where almost all capacitive coupling of RF power is eliminated by the Faraday shield. These electrons help in initiating inductive discharge (figure 1B) at power levels as low as 150 W, which otherwise would require more than 350 W of RF power and 0.1 mbar of gas pressure. A faint capacitive discharge co-exists in upper chamber along with strong inductive discharge in the lower chamber without really introducing any plasma potential fluctuations in the plasma of lower chamber. Low plasma potential obtained due to pure inductive discharge in the lower chamber helped in extending the ion source life. This configuration of ion source has been under use for more than 450 hours and there has not been any deterioration in the performance. With 160W of RF power, extracted Ar current density of more than 45 mA/cm^2 has been achieved.

ENERGY SPREAD MEASUREMENT OF EXTRACTED ION BEAM

For FIB applications, it is important to generate the ion beams with very low energy spread. The Energy spread contributes to chromatic aberration which is the variation of focal length with energy of particles being focused. Energy spread measurements on plasma bound ions and

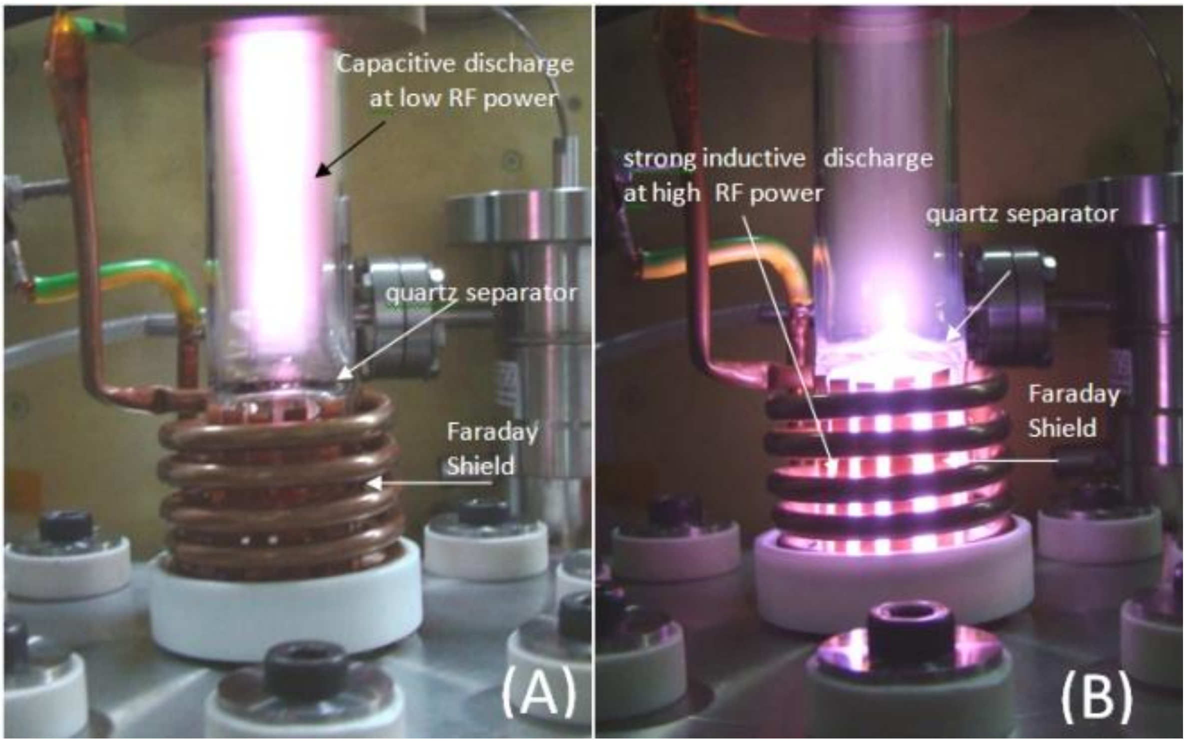

Fig 1. Operation of double plasma chamber. Capacitive discharge in upper chamber at low RF powers and strong inductive discharge in lower chamber at higher powers.

extracted ions were carried out using retarding field energy analyzer (RFEA) [3]. The planar gridded RFEA has the best resolution only for those ions that have trajectories parallel to the axis of the analyzer. In addition, with beams of larger divergence and higher energies, measurements yield poorer resolution. To minimize these errors in the measurements, an RFEA with focusing electrode which makes the diverging beam parallel before analyzing, was designed. With the use of focusing electrode there is significant improvement in the measurement accuracies. Measurements show that upto 160W of RF power, plasma bound and extracted ions have less than 5 eV energy spread and could achieve 2.6eV energy spread for 2.5 KeV Argon beam when ion source was operated at RF power of 50 W and gas pressure of $2x10^{-2}$ mbar [4].

ION BEAM FOCUSING COLUMN

Electrostatic lenses are used in forming finely focused beam. Focusing column consists of two einzel lenses. First lens is used to operate the column in various modes such as high current mode or high resolution mode. Extracted beam is allowed to freely drift over a distance of 40 mm and made to pass through an aperture of 1 mm to cut down the diverging beam. This beam is either focused or made parallel and passed through an aperture of 250 µm diameter. Fine aperture allows only the central core of the ion beam having divergence of less than ± 1.25 mrad to pass through the second Einzel lens and minimizes the contribution of aberrations to the beam spot size. The second lens focuses the ion beam at image plane (working distance) 1 mm away from second lens. Focusing column and all the electrodes of lenses are precisely machined with dimensional tolerances within ±10 µm. An ion beam deflectors are under fabrication to finely align the beam to the axis.

The diameter of ion beam and the ion beam profile at the focal plane are measured by moving the sharp knife edge across the ion beam and recording the ion beam from Faraday cup [4]. Knife edge measurements show that the ion beam profile is Gaussian and has 1.5 µm diameter (20%-80%) with current densities of >350mA/cm^2. By measuring the beam profiles at different heights beam divergence of 0.9 mrad was obtained. Under these operating conditions, the virtual source size is about 5-8 µm. With these values, angular current density and source brightness of ~10mA/cm^2 and $1x10^5$A/cm^2-sr-eV respectively were achieved.

MICRO MACHINING OF SURFACES

4KeV to 6KeV Ar ion beams were used in micromachining several patterns on silicon wafer. Instead of scanning ion beam, the translation stage is moved to create desired patterns. LabVIEW based application is written to control the translation stage. As deep milling requires slow movements, stage is moved rather than scanning the beam and thus avoiding the aberrations due to deflection. This enables to create micro patterns on large area on the sample. With about 20 nA of beam, Milling rates of more than 1 μm^3/sec were obtained. Fig 2. shows the AFM images of three circular holes milled

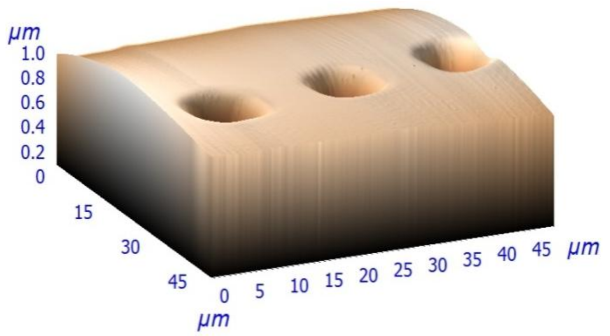

Fig. 2 circular features milled on Si wafer with different doses.

with different doses. The depth profiles of the holes obtained across the centre of the pattern shown in Fig. 3, which are nearly Gaussian shapes. Milled patterns show much wider features than the measured ion beam dimensions due to resputtering and redeposition. Various regular and complex patterns are created on Si wafer [5]. Further, micro-drilling in thin Cu foils were also successfully carried out. Work is in progress in using different lens configurations to achieve high current density and submicron beams.

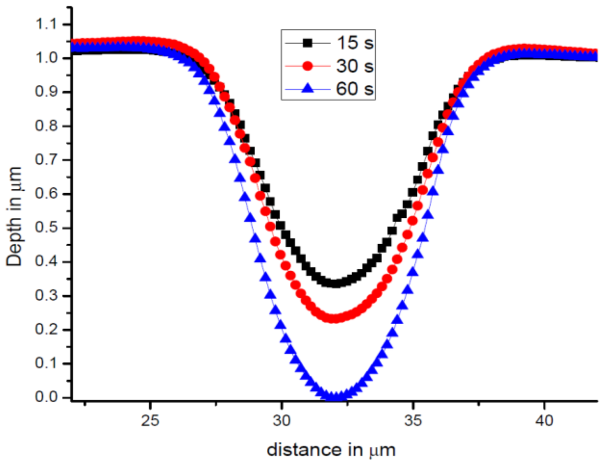

Fig 3. Depth profile of patterns created by Ar ion ion exposure for 15, 30 and 60 seconds respectively.

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