Novel Ion Beam Tools for Nanofabrication

Q. Ji\textsuperscript{a, 1}, X. Jiang\textsuperscript{a, b}, L. Ji\textsuperscript{a, b}, Y. Chen\textsuperscript{a, b}, B. v. d. Akker\textsuperscript{c}, K.-N. Leung\textsuperscript{a, b}

\textsuperscript{a} Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720
\textsuperscript{b} Department of Nuclear Engineering, University of California, Berkeley, CA 94720
\textsuperscript{c} Department of Physics, San Francisco State University, San Francisco, CA 94132

ABSTRACT

The drive towards controlling materials properties at nanometer length scales relies on the availability of efficient tools. Currently, high resolution ion beam processing is limited to direct-write techniques with mostly gallium ion beams, or the use of pre-structured masks. In this paper, several novel ion beam tools that have been developed at Lawrence Berkeley National Laboratory (LBNL) are reviewed: Maskless Micro-Ion-Beam Reduction Lithography system, Multiple Focused Ion Beam (FIB) system and ion beam imprinter, and a FIB/SEM dual beam system. With the availability of multicusp plasma ion sources, these ion beam tools can provide versatile ion beams in nanometer scale for future integrated circuit manufacturing, thin film media patterning, and micromachining.

Keywords: ion projection lithography, focused ion beam, ion beam imprinter, maskless lithography

1 INTRODUCTION

Current research to understand the science associated with nanoscale structures has shown the need for new approaches to the fabrication of future small-scale devices. For the last several decades, ion beams have played a significant role both in material modification (e.g., ion implantation, and micromachining) and analysis (e.g., secondary ion mass spectrometry). Conventional FIB systems, which utilize liquid gallium ion sources to achieve nanometer resolution, severely limit some applications and fundamental studies due to gallium contamination. Demands have been continuously increasing for ion beam tools with a variety of ion species in selectively doping or surface modifications in nanoscale device structures.

In this paper, several novel ion beam tools that have been developed at Lawrence Berkeley National Laboratory (LBNL) are reviewed: Maskless Micro-Ion-Beam Reduction Lithography system, Multiple Focused Ion Beam (FIB) system and ion beam imprinter, and a FIB/SEM dual beam system. With the availability of multicusp plasma ion sources, these ion beam tools can provide versatile ion beams in nanometer scale for future integrated circuit manufacturing, thin film media patterning, and micromachining.

2 MULTICUSP PLASMA ION SOURCES

Multicusp ion sources have been used for many applications, such as neutral-beam injectors for fusion devices, particle accelerators, ion implantation systems, compact neutron tubes, and proton therapy machines.[1, 2] Ions of virtually all elements in the periodic table can be generated by either filament dc discharge or RF induction discharge. Compact RF-driven ion sources have been developed for various ion species production, such as H\textsuperscript{+}, He\textsuperscript{+}, Ar\textsuperscript{+}, O\textsuperscript{+}, B\textsuperscript{+}, P\textsuperscript{+} etc. [3]. Besides gaseous elements, they can also be employed to produce metallic ions, e.g. Cu\textsuperscript{+}, Ni\textsuperscript{+}, Cr\textsuperscript{+}, Pd\textsuperscript{+},[4] and molecular ions, e.g. C\textsubscript{60}\textsuperscript{+}. A large area and uniform plasma is achievable with the multicusp ion source by arranging the magnets around the source chamber in such a way as to generate line-cusp magnetic fields. By optimizing the source configuration and extractor geometry, beam brightness as high as 440 A/cm\textsuperscript{2}Sr has been measured, which represents a 30 times improvement over prior work.[5] The ion beam systems described here are all developed based on this type of ion sources.

3 NOVEL ION BEAM TOOLS FOR NANOFABRICATION

3.1 Maskless Micro-Ion-Beam Reduction Lithography (MMRL) system

The manufacture of CMOS integrated circuits will eventually require techniques for patterning sub-10 nm features, with sub-25 nm half-pitch. Mask costs for deep-UV (eventually EUV) lithography will continue to escalate with each new generation of technology, and will even become prohibitive for low-volume IC products. Maskless patterning techniques are desirable in order to circumvent these issues.

A proof-of-concept maskless ion beam lithography machine called Maskless Micro-beam Reduction Lithography system has been developed in Lawrence Berkeley National Laboratory.[6-8] The MMRL system (Figure 1) uses inductively coupled rf multicusp plasma source to generate helium or hydrogen plasma, which has uniform density over a large volume. A mask or a pattern generator is directly placed on the plasma electrode. Due to the low ion energy inside the plasma source, less than 3V biasing voltage can switch ion beamlets on and off. The
The prototype MMRL system has eight electrostatic electrodes to accelerate ion beams to 75 keV and to reduce the beam size by 10X. A limiting aperture (Figure 2) is placed on the beam cross-over position to limit ion beam half angle and reduce the geometrical and first-order chromatic aberrations. Because of the small wavelength of ion beams, much smaller NA can be used in ion beam lithography machines, which gives much larger exposure field size than direct-write e-beam systems.

Figure 1: Maskless Micro-Ion Beam Reduction Lithography System uses a universal pattern generator (beam-forming electrode) to form lithographic patterns on wafers.

Figure 2: In the MMRL system, a limiting aperture is inserted at the beam cross-over plane for aberration reduction.

The MMRL tool can work in projection and maskless mode. Sub-100 nm resolution (Figure 3) has been demonstrated on the prototype MMRL system in projection mode. Employing the switchable pattern generator on the beam-forming electrode plane and combining the scanning of the high precision stages, the MMRL can perform multiple-beam maskless lithography and offer a possible solution for low-cost advanced ASIC fabrication.

A pattern generator, which can individually switch ion beamlets on and off, is being fabricated in the microfabrication laboratory of UC-Berkeley. Figure 4 shows a schematic diagram of the pattern generator. The heavily boron doped silicon layer faces the plasma side. Under the conductive P⁺ layer, there is a thermally grown SiO₂ insulation layer. A metal layer is then deposited under the insulation layer. The metal layer is patterned into lines and pads so that biasing voltages can be individually applied to each beam-forming aperture.

Figure 3: Ion beam exposure results on PMMA resist.

Figure 4: Switchable pattern generator for MMRL system.
3.2 Multiple Focused Ion Beam (FIB) system and Ion Beam Imprinter

Throughput is always an issue for focused ion beam system. In order to achieve higher throughput, parallel processes using multiple beamlets system is one of the promising solutions. Figure 5 shows the schematic diagram of a multiple focused ion beam system which employs a multicusp plasma ion source. As mentioned above, the ion source can generate uniform and large area plasma, therefore, only one source is needed to generate multiple beams. The pattern generator used in the MMRL system can also be employed as extraction electrode. Individual beamlet can be switched off simply by applying +10V on the extraction electrode relative to the source. A stack of electrodes with multiple apertures, which act as lens element, can further accelerate the ions to the desired energy, and then focus to a small beam spot at the target. Maskless lithography will be realized by switching the ion beamlets on/off and scanning the substrates in x and y directions.

![Schematic diagram of a multiple focused ion beam system](image)

Figure 5: (a) Schematic diagram of a multiple focused ion beam system. (b) Schematic diagram of the ion beam imprinter.

As illustrated in Figure 6, a stencil mask that consists of different features, such as lines, arcs, round holes, and other arbitrary shapes can also be used as a plasma electrode. In this case, ions extracted through the aperture reach the sample with the same pattern as those on the mask. This ion-beam imprint technique can transfer patterns not only onto a planar target, but also onto non-planar surfaces, for example the outer and inner surfaces of cylinders, which have numerous applications in micromachining and surface topology modification.[9]

![Schematic diagram of the ion beam imprinter](image)

(a) Schematic diagram of the ion beam imprinter. (b) Microscopic image of the arc (left) and rectangular (right) shape feature milled on the sample using ion beam imprinting.

3.3 A FIB/SEM dual beam system

Lack of integrated diagnostics in conventional systems also limits the information available from nanofabrication experiments. An integrated FIB/SEM dual-beam system will not only improve the accuracy, resolution and reproducibility when performing ion beam sculpting[10] and direct implantation processes, but also enable researchers to perform cross-sectioning, imaging, and analysis with the same tool.[11,12]

As shown in Figure 7, the FIB/SEM dual system developed between Harvard University and LBNL for direct doping or surface modification employs a mini-RF driven plasma source to generate focused ion beam with various ion species, a FEI two-lens electron (2LE) column for SEM imaging, and a five-axis manipulator system.[13] The mini-RF plasma source consists of a 1.5 cm inner diameter ceramic chamber and two layers copper wire as external antenna. Ion beams are extracted through a 50-µm-diameter extraction aperture. Ar⁺ ion current density as high as 100 mA/cm² has been obtained with only 150 W of input RF power. An all-electrostatic two-lens column has been designed to focus the ion beam extracted from the source. Based on the ion optics simulation, beam spot sizes as small as 100 nm can be achieved at beam energies between 5 to 35 keV if a 5-µm-diameter extraction aperture is used.
Smaller beam spot sizes can be obtained with smaller apertures by sacrificing some beam current. The FEI 2LE column, which utilizes Schottky emission, electrostatic focusing optics, and stacked-disk column construction, can provide high-resolution (as small as 20 nm) imaging capability, with fairly long working distance (25 mm) at 25 keV beam voltage. The picture of the FIB/SEM dual beam system after assembly is shown in Figure 8. A major advantage of this tool is the ability to produce a wide variety of ion species tailored to the application.

Figure 7: Schematic diagram of the FIB/SEM dual beam system.

Figure 8: A picture of the FIB/SEM dual beam system.

4 SUMMARY

Several ion beam tools have been developed to provide ion beams at nanometer scale with choices of a variety of ion species. They not only can be applied to many research areas including nanostructure patterning, selectively doping, and surface modification, but also will open up new opportunities in nanofabrication and analysis.

5 ACKNOWLEDGEMENTS

The work is supported work is supported by DARPA and the U.S. Dept. of Energy under Contract No. DE-AC03-76SF00098 and National Science Foundation under contract No. DMR-0216297. Support from staff members of the Plasma and Ion Source Technology Group in Lawrence Berkeley National Laboratory is also gratefully acknowledged.

REFERENCES


Email: Qji@lbl.gov, PHONE: 510-486-4802, FAX: 510-486-5101.