MOTIS: A Focused Ion Beam Source Based On Laser-Cooled Atoms

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Abstract. We have demonstrated high resolution focused ion beams based on a magneto-optical trap ion source (MOTIS), which takes advantage of the ultra cold temperatures of laser cooled atoms to produce high brightness, low emittance ion beams. We have created focused beams of both Cr^+ and Li^+ and present secondary electron micrographs obtained with these beams, demonstrating a focal spot size as low as 27 nm at a beam energy of 2 keV. This work shows that the MOTIS can be a useful source for focused ion beams that will open new opportunities for applications in materials characterization and metrology.

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INTRODUCTION

High resolution focused ion beams (FIBs) are one of the most important tools for characterization and metrology in nanoelectronics. Beams of ions focused to the nanometer scale enable essential tasks such as three-dimensional metrology, defect detection and failure analysis, and make possible important procedures such as transmission electron microscope (TEM) lamella preparation, in-situ editing of integrated circuits and mask repair. These applications are enabled by a FIB's ability to not only image a surface by generating secondary electrons or backscattered ions, but also remove and add material via sputtering or interaction with chemical precursors.

Over the past three decades, the generation of high resolution FIBs has been largely accomplished via the liquid metal ion source (LMIS)[1]. This source uses field ionization from a sharp tip coated with liquid metal to generate a high brightness beam of ions (most often Ga^+) that is then apertured, accelerated, and focused to the nanoscale. Recently, new ion sources have begun to appear. Field ionization of He gas from a specially prepared sharp tip has been demonstrated[2], and is now available commercially. Also, a plasma-based source has been introduced[3], which offers high ion currents of heavier noble gas ions such as Xe^+ at the expense of slightly less resolution.

All FIB systems in use today have some characteristics in common. Generally, a high beam energy of at least 10 kV is required to achieve nanoscale resolution, and the variety of ionic species that can be reliably produced is limited. High energy is required both because most sources have a large energy spread which gives rise to chromatic aberrations in the focused beam, and also because field ionization requires a large electric field. Species limitations arise because of a range of practical considerations: only Ga and a few alloys have the necessary wetting characteristics to make a robust liquid metal ion source; He and perhaps Ne are the only ions that can be produced in a gas field ionization source because of tip contamination issues; and plasma sources are essentially limited to gas phase materials.

While FIBs enjoy a wide range of applications already, their utility could be dramatically enhanced if they could be realized with lower beam energies and with a wider choice of ionic species. High beam energy can lead to deep implantation of ions and undesirable contamination of the sample. It also increases sputtering and surface damage, resulting in altered samples, roughened lamellae, and limitations on resolution in imaging. Lack of choice of species

also can lead to undesired excessive sputtering and unwanted contamination issues. Heavy ions such as Ga^+ have a much higher sputter rate than light ones, and can create problematic contamination when, for example, they are used in mask repair or to fabricate nanoscale magnetic structures. At low energies, beam-assisted chemistry can also be affected by the chemical nature of the ion being used, and having a choice of ions could allow a great deal of flexibility in process optimization.

MAGNETO-OPTICAL TRAP ION SOURCE

Recently, a new ion source has been proposed that opens new possibilities for producing FIBs with low beam energy from a broad range of ionic species. The magneto-optical trap ion source (MOTIS) achieves a low emittance and a high brightness, sufficient for focusing the ions to the nanometer scale, in a manner very different from other sources. Whereas field ionization sources rely on an extremely small source area to keep the emittance small, the MOTIS takes advantage of the extremely low temperatures of laser-cooled atoms to achieve the same end. By photoionizing cold atoms, a beam of ions is created with a very small transverse velocity spread, which results in a very small angular spread for the beam. Since the emittance of a source is proportional to the product of the beam size and its angular spread, a beam with very low emittance is created, even though the transverse dimension is not particularly small. The cold temperature of the atoms also leads to an extremely small fundamental limit for the energy spread. In most cases this fundamental limit is not reached, however, because the ions are extracted in a potential gradient which introduces a small but manageable energy spread. Regarding selection of ionic species, the MOTIS is essentially compatible with any atom that can be laser-cooled, a list which includes alkalis, alkaline earths, noble gases and several metals – over 20 species in all[4]. It is also worth noting that the MOTIS creates isotopically pure ion beams because the laser cooling process spectroscopically selects only one isotope at a time.

A number of theoretical analyses of the MOTIS and similar sources have been carried out, predicting a high level of performance[5-7], and several realizations have been reported. A Cr MOTIS[8] was measured to have an emittance as small as 6×10^{-7} mm mrad $MeV^{1/2}$, a value competitive with the LMIS. Measurements of the energy spread of ion bunches from a pulsed Rb MOTIS[9] showed values as low as 0.02 eV, over two orders of magnitude smaller than the energy spread in the LMIS. Rudimentary images

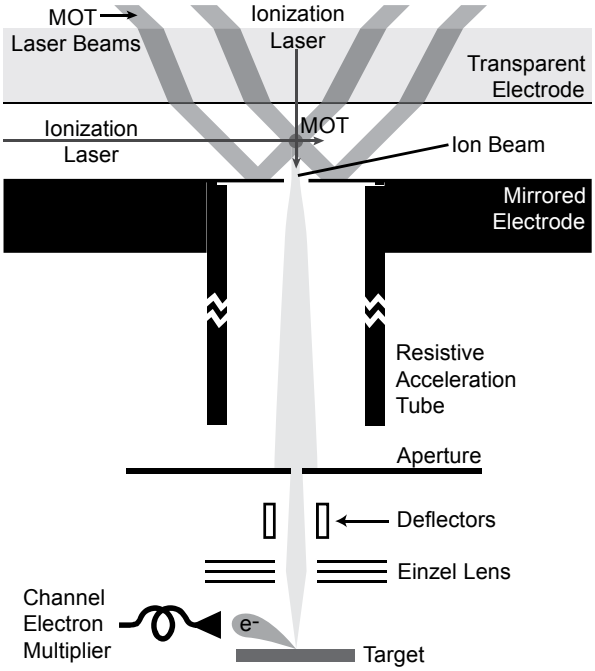

FIGURE 1. Magneto-optical trap ion source FIB system. Neutral atoms from a light-force-slowed atomic beam (not shown, incident horizontally in the figure) are trapped in a magneto-optical trap (MOT) and ionized with a laser incident either transverse to or along the ion beam axis. Ions are extracted by an electric field between a transparent and a mirrored electrode, accelerated in a resistive tube, and deflected and focused in a conventional ion optics column.

were reported using a focused Cr ion beam from a MOTIS[4], and detailed calculations and measurements of the influence of inter-ion Coulomb interactions was carried out for a Li MOTIS[10].

A schematic of a MOTIS is shown in Fig. 1. A magneto-optical trap (MOT)[11] is formed at the zero of a quadrupole magnetic field, which is generated by two opposing ring-shaped NdFeB permanent magnets (not shown). Three pairs of counter-propagating laser beams, tuned slightly below an atomic resonance in the atomic species to be trapped, provide trapping and cooling forces. Atoms are loaded into the trap from an atomic beam that has been slowed using a Zeeman slower, which consists of a counter-propagating near-resonant laser beam and a tapered magnetic field[12] (not shown). Under typical operating conditions up to 10^8 atoms are held in the trap within a diameter of a few hundred micrometers and a temperature of a few hundred microkelvin. The load rate of the trap is typically in the range of 10^8 s^{-1} to 10^9 s^{-1}.

The MOT is located midway between two flat electrodes, to which a voltage is applied to create an extraction field. The upper electrode is made from fused silica with an indium tin oxide transparent

conductive coating, and the lower electrode is coated with aluminum to form a mirror. Two of the counter-propagating laser beam pairs that form the MOT are incident through the transparent electrode and are reflected from the mirrored electrode (see figure). The third pair, not shown in the figure, is incident in a perpendicular direction. An ionization laser beam, tuned to have just enough energy to ionize the excited state atoms in the MOT without causing excess heating, is incident either between the electrodes transverse to the extraction direction (transverse ionization), or through the transparent electrode along the extraction direction (axial ionization).

Ions extracted from the intersection of the ionization laser and the MOT travel through a small hole in the mirrored electrode and are accelerated in a resistive acceleration tube, which brings the ions to the desired beam energy gradually over a distance of several hundred millimeters, with minimal focusing of the beam. After exiting the acceleration tube, the ion beam is apertured, deflected, and focused via conventional ion optical elements.

Cr MOTIS

As an initial test of the use of a MOTIS in a focused ion beam, we have constructed a Cr-based system. Cr is a relatively light metallic element that, when formed into a focused ion beam, could enable deposition and removal of conductors, improved mask repair, and formation of optical, electronic and magnetic devices through controlled implantation.

In our experiment, ^{52}Cr was cooled with laser light tuned to the $^7S_3 \rightarrow {}^7P_4$ transition at 425 nm, obtained from a continuous-wave (CW) Ti:sapphire laser doubled in an external build-up cavity. The MOT laser beams had $1/e^2$ diameters of 4 mm and contained a power of a few milliwatts each. Ionization laser light at 320 nm was provided via a CW dye laser operating at 640 nm with DCM laser dye followed by an external cavity doubler. The atomic beam was produced by thermal evaporation from an effusion cell.

Fig. 2 shows an image obtained by rastering the focused Cr^+ ion beam across a sample and collecting secondary electrons. The sample in this case is the surface of a microchannel plate, which consists of a hexagonal array of 10 μm-diameter holes in metal-coated conductive glass. The MOTIS was used in axial ionization mode for this image, with the ionization laser focused to a beam waist of approximately 10 μm $1/e^2$ diameter. The beam current was approximately 0.2 pA. The voltage was 4000 V on the transparent electrode and 3840 V on the mirrored electrode, resulting in a 3920 eV beam energy. These voltages were chosen so that the weak lens formed at the exit of the ionization region was slightly diverging, resulting in a beam that filled the focusing lens to a level that gave the optimum balance between aberration and emittance contributions to the focal spot size. The working distance was 17 mm.

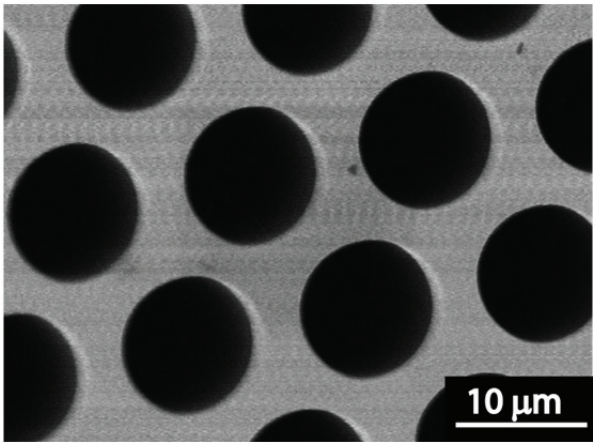

FIGURE 2. Secondary electron image of a microchannel plate surface obtained by scanning a focused Cr ion beam from a MOTIS. Ion beam energy is 3.9 keV and beam current is 0.2 pA.

Li MOTIS

With ion microscopy in mind, we have also realized a MOTIS using Li^+ ions. Lithium is of particular interest for several reasons. It is a very light ion, so it is expected to create minimal sputtering damage during imaging. High Li^+ backscattered ion yield, due to its low neutralization probability at the surface, enhances surface-sensitive imaging based on backscattered ion detection, which may lead to new contrast mechanisms. Li also diffuses quite readily, going interstitial in many materials, so it may be less likely to create local contamination and structural damage via implantation. In addition, its chemical reactivity may prove useful in beam chemistry applications. A further motivation is that atomic beams of Li are easily produced in a moderately heated effusion cell at a few hundred degrees Celsius, and the laser light needed to cool and trap Li is readily available via laser diode systems.

In our realization, ^{7}Li laser cooling was achieved via the $2^2S_{1/2}$ (F=2) $\rightarrow$ $2^2P_{3/2}$ (F'=3) hyperfine transition at 671 nm. Another laser frequency, offset by 803 MHz to match the F=1 $\rightarrow$ F'=2 hyperfine transition, was superposed on all cooling beams to return atoms that had decayed into the F=1 hyperfine state back to the F=2 $\rightarrow$ F'=3 system. We produced the necessary laser light in a laser-diode-tapered-

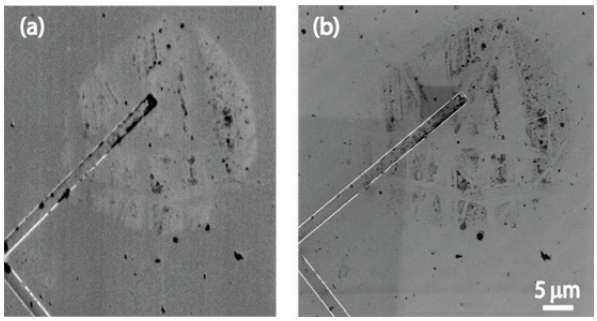

FIGURE 3. Secondary electron images of unknown contamination on a Si wafer. (a) Li FIB image, using 2 keV ions. (b) SEM image, using 1 keV electrons.

amplifier system. The light was first split into two equal-power components, one of which was shifted by 803 MHz. The two beams were then recombined and redivided into the necessary MOT and slower beams using a fiber optic combiner/splitter assembly. The ionization laser beam at 350 nm was obtained from a Ti:sapphire laser with an external cavity doubler. All laser light was transported to the MOTIS vacuum chamber via fiber optic cables.

To construct a prototype FIB, we used a commercial FIB system, replacing the liquid metal ion source with the Li MOTIS and deactivating the first lens, whose original function was nominally to collimate the initially divergent LMIS beam. The beam energy was chosen to be approximately 2 keV, set by the mean voltage of the transparent and mirrored electrodes. As with the Cr MOTIS, the voltage difference between these plates was chosen to create a slightly diverging lens that provided the optimum beam diameter at the focusing lens, balancing aberrations with source emittance contributions to the focal spot size.

Fig. 3a contains an example of a micrograph taken with the Li^+ FIB. Shown is a region of a silicon wafer with an area of unknown contamination. For comparison, we show a scanning electron micrograph (SEM) of the same region. Of particular note is the fact that in the Li^+ ion micrograph the contamination shows up white, whereas it appears black in the SEM. This highlights the possibility of new contrast mechanisms that could be realized by imaging with an ion such as Li^+ instead of electrons.

Fig. 4 shows images taken at high resolution with the Li^+ FIB. These images illustrate the capability of the Li MOTIS to achieve extraordinarily high resolution at a low beam energy of 2 keV. Fig. 4a is a micrograph of a graphite sample, which is often used as a resolution target because it is sputter-resistant and has structure on a wide range of length scales. Fig. 4b is an image of a tin-on-carbon SEM resolution test

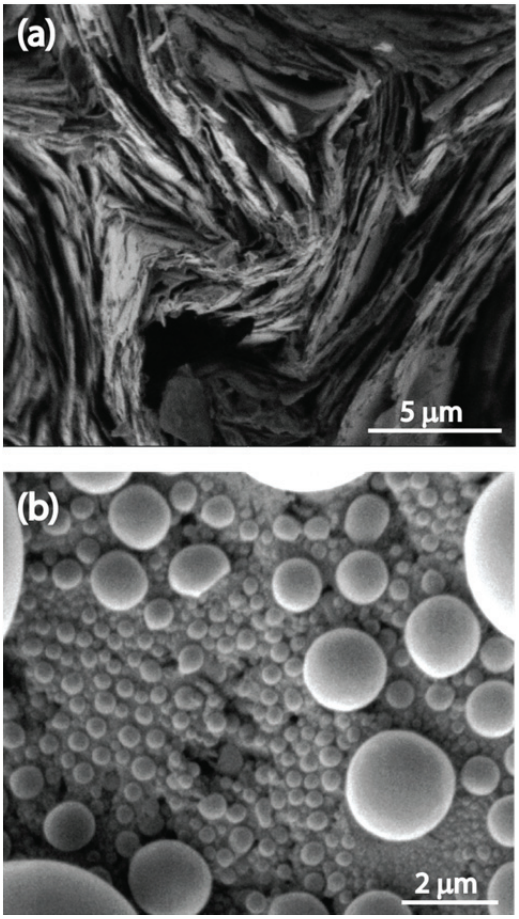

FIGURE 4. Li MOTIS high resolution secondary electron images, (a) graphite, and (b) tin balls on carbon. Li^+ beam energy was 2 keV and current was approximately 1 pA.

specimen. Both images were taken with a beam current of approximately 1 pA.

To quantify the resolution of the 2 keV Li^+ FIB, we also conducted measurements using a knife edge[13] under conditions similar to those used in Fig 4. By sweeping the beam across the edge of a cleaved <100> silicon wafer, we were able to determine a 25 % to 75 % rise distance of (26.7 ± 1.0) nm (uncertainty is one standard deviation combined standard uncertainty). This represents an unprecedented level of resolution for a 2 keV ion beam.

CONCLUSION

We have demonstrated a new type of ion source that has the potential to impact a wide range of applications in characterization and metrology of nanoelectronics. Choosing two out of a wide range of possible ionic species, we have constructed magneto-optical trap ion sources and shown that low energy

focused ion beams with nanoscale resolution and significant beam current can be produced.

The results presented here suggest that a number of new applications will be forthcoming. For example, new capabilities in 3D metrology and defect detection will be enabled not only by the ability to mill at high resolution leaving very smooth surfaces without contamination, but also by the possibility of elemental analysis via low-energy ion scattering[14] or secondary ion mass spectroscopy (SIMS). Ultrathin TEM lamellae with very smooth surfaces may become possible as well. In addition, new methods for circuit edit and mask repair may be forthcoming.

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