New Ion Source for High Precision FIB Nanomachining and Circuit Edit

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Abstract

We present a review of the Low Temperature Ion Source (LoTIS): its aims, design, performance data collected to date, and focused spot size projections when integrated with a FIB. LoTIS provides a Cs^+ beam that has been measured to have high brightness ($> 10^7 \mathrm{Am^{-2}sr^{-1}eV^{-1}}$), and low-energy spread ($<$ 0.5 eV). These source characteristics enable a prediction of sub-nm focused spot sizes. A FIB with the capabilities enabled by LoTIS would be well-suited to addressing FIB failure analysis tasks such as nanomachining, circuit edit, and site-specific SIMS.

Introduction

The rapidly shrinking pitch sizes in modern integrated circuits mean that circuit edit, and associated techniques employing the focused ion beam (FIB), may not be viable within a few years[1]. These techniques play an important role in reducing the number of iterations required between the design of a new prototype chip and its large scale fabrication. Existing circuit edit methods would be enhanced by access to a FIB with smaller focal spot sizes, higher sputter rates, and reduced implantation depth. Specifically, if focal spot sizes could be reduced to the sub-nm regime, then the viability of the many circuit edit and failure analysis techniques would be extended for at least several years.

In order to obtain improved FIB performance, it will be critical to develop a better ion source. This is because in a modern FIB the ion source is the performance defining element. Secondary ion mass spectrometry (SIMS) techniques employed in failure analysis would also stand to benefit from an ion source with high brightness that can also provide a high yield of secondary ions for a variety of substrates.

With these motivations in mind, we present results from early measurements on a new Cs^+ low-temperature ion source (LoTIS). These measurements allow credible projections of FIB performance enabled by LoTIS. These projections include sub-1 nm spot size capabilities at 1 pA in a 30 kV beam and total currents from below 1 pA up to several nanoamperes. When compared with the liquid metal ion source (LMIS), the LoTIS will offer reduced spot sizes at beam energies below 30 kV and beam current of roughly 1 nA or less. LoTIS will also offer improved sputtering efficiency and a wider range of currents – up to several nanoamperes – in comparison with the helium or neon gas field ion sources. In the case of SIMS, it will offer much higher beam currents at equivalent spot sizes when compared with the Cs^+ ‘frit’ ion sources used today.

In the following, a schematic description of LoTIS’s major components will be given. The source description is followed by a presentation of previously published measurements on LoTIS brightness and energy spread. We note that, to date, LoTIS has not been integrated with an ion acceleration and focusing column. Despite this, our measurements of brightness and energy spread enable us to present credible predictions of the source’s spot size for a hypothetical column. Predicted spot sizes will be shown for a variety of beam currents and beam energies. The paper will conclude with a list of the next steps to be taken on the road to integrating LoTIS into commercial FIB instruments.

Brightness and Energy Spread Measurements

LoTIS creates positive ions via the laser photoionization of a gas of neutral atoms; the ions are then accelerated into a beam by an applied electric field. The normalized brightness [2] of such an ion source may be written:

$$B = \frac{J}{\pi k_B T}$$

where J is the cross sectional current density of the ion beam and T is the temperature of the ions. Increasing the brightness of LoTIS, as with any ion source, may be achieved by increasing ion current density or reducing ion temperature.

Brightness is a good measure of ion source performance because it is largely conserved along the beam line and can be used to predict focused spot size performance (when combined with the parameters of a given ion focusing column). Brightness can also be used as a way of comparing the performance of systems equipped with different ion sources. Simple formulas [3] can be employed to obtain an estimate of the achievable spot sizes in systems with known brightness, energy spread and beam energy.

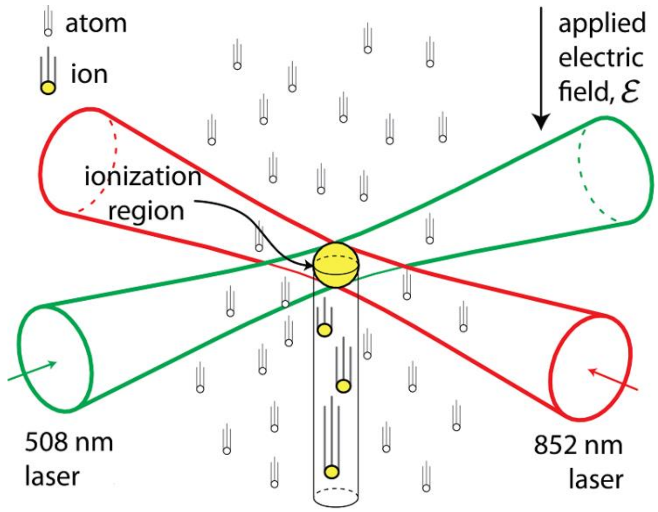

Figure 1 Ionization laser geometry, showing the overlapping 852 nm 508 nm lasers driving the two-step photoionization.

LoTIS produces a high brightness ion beam by generating very low temperature ions. The ions have a low temperature owing to two facts:

1. Laser cooling techniques [4] are applied to bring gaseous neutral atoms from room temperature (or hotter) down to micro-Kelvin temperatures.
2. For a properly configured set of ionization lasers, the temperature of the ions will be equal to that of the neutral atoms from which they were created

While not all atomic species are compatible with LoTIS technology because many are not amenable to laser cooling, quite a few are suitable. The alkalis may all be readily cooled, as may the noble gases and several other metals such as chromium and erbium. Reductions in temperature to below 100 μK are achievable with a few of these atomic species. Switching between atoms in the same system is in principle possible, but it does present significant challenges, since each atom requires its own set of lasers for cooling and photoionization. Additionally, densities and temperatures achievable vary greatly between elements, so it is not presently clear which of these species (besides cesium) may be used to create a LoTIS with a brightness larger than that of the industry standard LMIS value of $10^6\,\mathrm{Am^{-2}sr^{-1}eV^{-1}}$. For these reasons our current efforts are focused exclusively on production of high-brightness Cs^+ ion beams.

Before describing LoTIS, we consider a simplified system where atoms in a gas of neutral cesium maintained at a fixed pressure in a vacuum chamber are photoionized as they pass through a sheet of light. The current density J in this case can be written as [5]:

$$J = \frac{\sqrt{2}P}{\sqrt{\pi M k_B T}} \tag{1}$$

where P is the pressure of the gas, and M is the atomic mass. For a pressure of $7 \times 10^{-4}\,\mathrm{Pa}$ $(5 \times 10^{-6}\,\mathrm{Torr})$ at room temperature, this implies a brightness (using equation (1)) that is less than $40\,\mathrm{Am^{-2}sr^{-1}eV^{-1}}$, which is many orders of magnitude smaller than the LMIS's. Achieving high brightness therefore requires either a large increase in current density or a large reduction in temperature. Laser cooling can provide the large reduction in gas temperature required to increase the system's brightness.

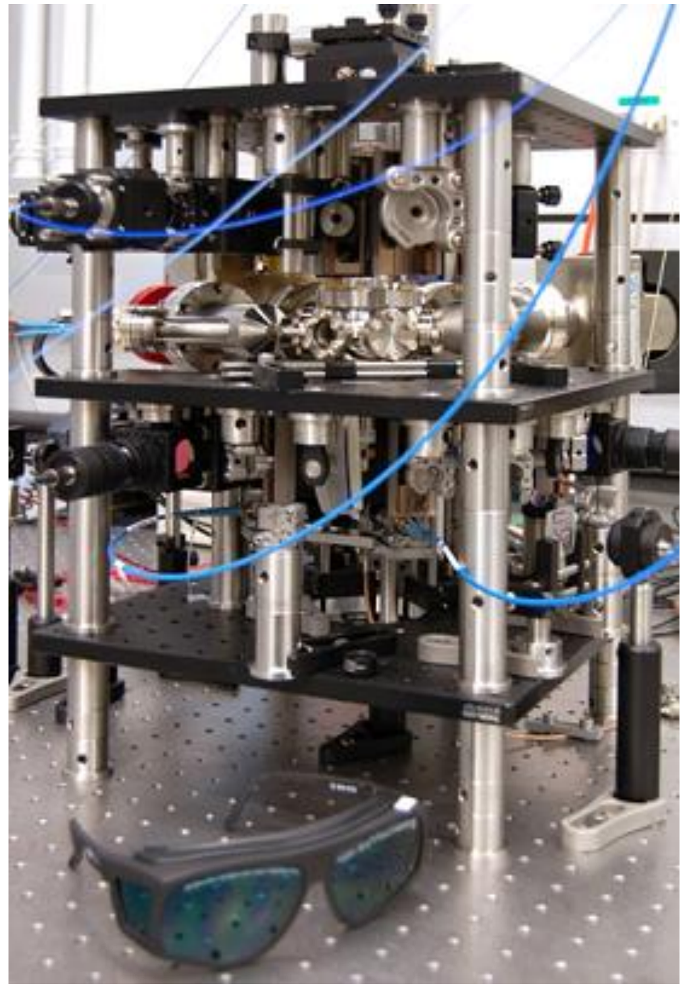

Figure 2: Photograph of Low Temperature Ion Source (LoTIS) prototype. Laser safety glasses included in foreground for scale. Lasers used to power the source are located on another table and light is carried to the source through fiber optics. The prototype shown includes all the components needed to create the ion source, but does not include an ion focusing column or a sample chamber

The approach taken by LoTIS is to create a high density beam of neutral cesium, cool it transversely to its axis, and then direct that beam through the photoionizing laser light. The reasons for this particular approach are detailed elsewhere [6]; in brief, we note that previously demonstrated ion sources employing laser cooling utilized a trapped gas of atoms. This approach limits the maximum brightness to of order $10^5\,\mathrm{Am^{-2}srad^{-1}eV^{-1}}$ owing to the limited rate of diffusion of atoms into the photoionization laser light[7]. By contrast, LoTIS employs a beam of atoms that flows through the photoionization region while remaining cold enough to achieve high brightness.

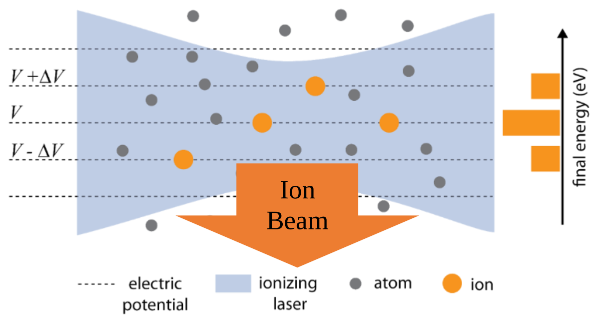

Figure 3 Schematic view showing the origin of the chromatic energy spread in LoTIS. Ions are created over a finite extent in a non-zero electric field. The differences in the potentials at which they are creates give rise to the chromatic energy spread.

The photoionization scheme requires two laser frequencies, and an isometric view of the ionization region is shown in Fig. 1. The configuration of the ionization lasers allows LoTIS to create only the amount of current desired for the task at hand. More tightly focused ionization lasers will lead to a smaller overlaps of the ionization laser beams and atom beam, resulting in lower currents. The highest achievable current will be reached when the all of the neutral atoms are ionized. Currents up to 5 nA have been achieved to date.

A photograph of the prototype ion source with which the brightness measurements were made is shown in Fig. 2. Laser cooling and photoionization light is carried to the LoTIS vacuum chamber through optical fibers. The laser light sources, frequency control and fiber launch optics are on an adjacent table (not shown).

A direct measurement of LoTIS brightness is challenging owing to its very low angular divergence. With the assumption that ion and atomic temperature are initially equal upon ionization, an initial (i.e., immediately after ionization) brightness of $2 \times 10^7\ \mathrm{Am^{-2}srad^{-1}eV^{-1}}$ can be calculated. While the above assumption is supported by previously taken data[8], a more definitive result could be obtained by focusing the ion beam in a source-limited (aberration free) configuration. This definitive measurement is the subject of current efforts.

After ionization, inter-ion forces may increase the temperature of the created ions. These effects on system brightness have been modeled in Monte-Carlo simulations incorporating all pairwise effects [6,9]. For an emission current of 1 pA and an extraction electric field of $10^5\ \mathrm{V/m}$ the effect of these interactions on ion temperature was found to be limited to less than 10% of the ions. The brightness of the remaining 90% of ions was greater than $10^7\ \mathrm{Am^{-2}srad^{-1}eV^{-1}}$. At higher currents, Coulomb effects lead to lower source brightness; simulations up to 1 nA have been performed, showing that the source maintains a brightness above $10^6\ \mathrm{Am^{-2}srad^{-1}eV^{-1}}$. At 1 nA, a field of order $2 \times 10^6\ \mathrm{V/m}$ is typically used. In each case, the use of higher electric fields will mitigate the effects of Coulomb interactions; however, this will come at the expense of a larger chromatic energy spread as explained below.

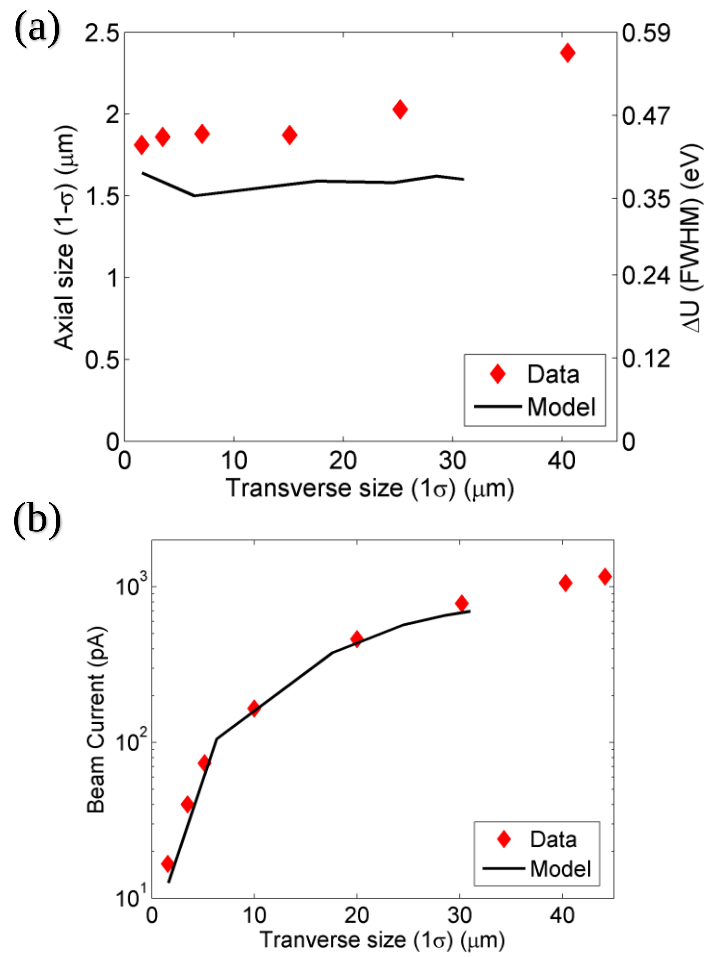

Figure 4 (a)A comparison of measured axial source size (left axis) and the equivalent energy spread at an applied field of 100 kV/m (right axis) versus the transverse size (one standard deviation, or 1σ) of the ionization lasers, which is proportional to beam current. Equipment limitations prevented model results at beam sizes larger than 30 µm. Random uncertainties are smaller than marker symbol. Systematic uncertainties are estimated to be less than 20% and include the effects of laser misalignment and aberrations in its intensity profile. (b) Total LoTIS beam current created versus transverse beam size. Random uncertainties are smaller than data symbol. Potential sources of systematic uncertainties from part (a) remain, but are expected to have a reduced impact on total current.

In LoTIS, the energy spread is equal to the product of the electric field used to accelerate the ions and the physical extent of the source along the direction of the field. This physical extent of the source along the electric field direction is determined mostly by the size of the ionizing laser(s), typically focused to a couple microns.

Figure 3 shows this concept schematically. With an electric field of order $10^5\ \mathrm{V/m}$, this implies an energy spread of a few tenths of an electron volt. Since the operator is free to choose a convenient field for ion extraction, the optimal choice (from the perspective of providing the smallest focal spot size) will depend on both the extracted current as described above and the chromatic aberration coefficients of the lenses in the focusing column.

The theorized energy spreads have been verified with a time-

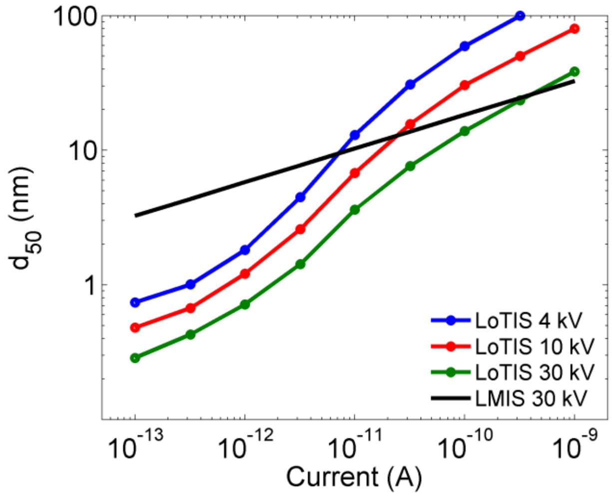

Figure 5 Projected performance of the LoTIS for beam energies of 4 kV, 10 kV and 30 kV, and LMIS data at 30 kV. d_{50} is the diameter into which 50% of the total beam current falls in the focal plane. The plot shows currents between 0.1 pA and 1 nA.

of-flight measurement. The photoionization lasers were pulsed on briefly and the time taken by ions to arrive at a downstream micro-channel plate was recorded. The electric fields in the vicinity of the source and downstream were configured such that there was a strong correlation between time of flight and the ion's initial position or, equivalently, final energy. Data were taken for several configurations of the ionization lasers. Each configuration corresponds to a differently-sized ionization volume. Less-tightly focused ionization lasers (in the transverse direction) lead to higher currents since they will ionize a larger fraction of the atomic beam. The measurement results are shown in Fig. 4. The right vertical axis is labeled with the beam's energy spread given a fixed applied field of 100 kV/m. Note, however, that in a real application the higher transverse sizes would be used to generate larger higher currents and hence would be used with a stronger extraction electric field. For this reason, the more relevant data for calculation of theoretically achievable spot sizes is the axial size of the source versus transverse size; this data is on the left Y axis.

Focused Spot Size Projections

The measurements of LoTIS brightness and energy spread enable theoretical spot size predictions to be made, given the parameters of a hypothetical ion focusing column. These calculations began with the output of the Monte-Carlo simulations described above. The output of these simulations yielded the positions and velocities for some tens of thousands of ions generated for a particular configuration of the atomic beam and photoionization lasers. The simulations incorporated ions with final beam energies between 1 kV and 40 kV and beam currents between 0.1 pA and 1 nA. Simulations were also carried out for a variety of accelerating fields between 10^4 V/m and 2×10^6 V/m. Checking the results for a variety of fields is important because, as noted above, the choice of field involves trading off the brightness reducing effects of Coulomb interactions against the source's chromatic energy spread.

For each of these simulation outputs the ions were then ray traced through a hypothetical ion focusing column incorporating spherical and chromatic aberrations. The aberration coefficients were taken to be $C_C = 30$ mm and $C_S = 100$ mm; these values are typical of those found in ion focusing elements used in many commercial FIBs.

Figure 5 shows the resulting spot size as a function of beam current extracted. For each beam energy and beam current the opening angle in the final lens and the accelerating field was chosen to optimize d_{50}, the diameter into which 50 % of the ions fall. Given the brightness and energy spread measurements presented above, it is projected that LoTIS will have superior performance to the LMIS at currents below 1 nA. Only LMIS data for 30 kV was found in the literature; however if similar data series for the LMIS were plotted for beam energies of 4 kV and 10 kV, the relative performance of LoTIS would be even more favorable at these beam energies owing to its smaller energy spread.

Conclusions

Measurements performed on LoTIS to date indicate that it has both a higher brightness and a lower energy spread than the LMIS for currents in the range of <1 pA up to at least 1 nA. A more definitive brightness measurement should be performed next using a focused beam. This would eliminate the need to make any assumptions about the ion temperature required to conclude the value of 10^7 $\mathrm{Am^{-2}srad^{-1}eV^{-1}}$ given above. This work will be performed as soon as the LoTIS prototype can be integrated with an ion focusing column. The time of flight energy spread measurement is subject to fewer uncertainties and is therefore known with greater confidence.

Assuming the reliability of the brightness measurements, the LoTIS's predicted focus spot sizes suggest that it will have better performance than alternative ion sources. Cesium's heavy mass (133 u) will make it an efficient sputterer. High mass combined with an ability to work at relatively lower beam energies without so large of an increase in focused spot size means LoTIS will operate with reduced subsurface contamination or damage. Together these facts suggest that LoTIS will be well suited to FIB nanomachining work requiring currents up to a few nanoamperes. To realize this potential the LoTIS must be integrated with a high performance FIB platform and ion focusing column.

Finally, we note that Cs^+ beams are also employed for their high rate of secondary negative ion generation in secondary ion mass spectrometry (SIMS) applications. LoTIS has a brightness several orders of magnitude higher than the industry standard Cs+ 'frit' source. For this reason LoTIS will also have the opportunity to improve performance in site-specific SIMS applications.

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