Advances in Source Technology for Focused Ion Beam Instruments

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Owing to the development of new ion source technology, users of focused ion beams (FIBs) have an increasingly wide array of uniquely capable platforms to choose from. Specifically, the new ion sources are able to offer superior performance in several applications when compared with the industry-standard Ga^+ liquid metal ion source. FIBs equipped with an inductively coupled plasma (ICP) ion source are better equipped to carry out large volume milling applications by providing up to 1 µA to 2 µA of 30 keV Xe^+ ions focused into a sub 5 µm spot. However, ICP FIB's are presently limited to 25 nm-30 nm imaging resolution at 1pA. The Gas Field Ionization Source (GFIS) relies upon an ion source that is the size of a single atom on the emitter, and correspondingly gains a high brightness through its very small source size. The high brightness allows the GFIS to produce a very small focused probe size (less than 0.35 nm for helium and <1.9 nm for neon), but with comparatively small beam currents (less than 2 pA). Other ion sources still being developed, such as the Cs^+ Low Temperature Ion Source (LoTIS), may enable high performance nanomachining with its projected sub-nm focal spot size at 1 pA, maximum currents of several nanoamps, as well as integrated secondary ion mass spectrometry (SIMS) capabilities.

Keywords: Ion Beam, Focused Ion Beam, FIB, Liquid Metal Ion Source (LMIS), SIMS, ICP, LoTIS, GFIS.

Introduction: Metrics of Ion Source Performance

Focused ion beam instruments serve a variety of distinct applications, and their capabilities depend very much upon their underlying ion source technology. The ion source technologies are characterized by the available ion species, emission stability, the beam current that can be attained within a given focused probe, and the size of the focused probe. The latter two characteristics rely critically upon the ion source's reduced brightness (measured in A m^{-2} sr^{-1} V^{-1}) and the energy spread (measured in eV). For each of the ion sources reviewed in this paper, these characteristics will be presented. For reference and comparison, the most widely used focused ion beam source, the gallium liquid metal ion source (LMIS), is characterized as follows[1]: The ion species available with the LMIS is principally gallium, and through active control schemes, such an ion source can be relatively steady for periods several days – depending on the usage. The reduced brightness of the gallium LMIS is usually cited as 10^6 A m^{-2} sr^{-1} V^{-1}

and the energy spread is about 5 eV. Conventionally, these gallium FIB system can achieve a small focused probe size of 5 nm when small currents of 1 pA are required. Focused beams with higher currents of 1 nA can be achieved with a larger probe size of 40 nm. The gallium LMIS is a mature technology with a variety of well-established FIB applications; whereas the three technologies reviewed in the following three sections are less mature and just now gaining commercial acceptance.

Inductively Coupled Plasma Ion Sources

Theory of Operation:

A cross-sectional schematic view of an ICP ion source is shown in **Figure 1**. The cylindrical plasma chamber has a solenoid antenna wrapped around its outside and a Faraday shield is positioned between the antenna and the plasma chamber.

A radio frequency current is passed through the antenna in order to create an azimuthal induction field in the outer skin of the plasma that causes plasma electrons to be accelerated. The RF frequency is significantly below the plasma's electron resonant frequency (a few gigahertz) and usually above the plasma's ion resonant frequency (a few megahertz), so as to cause the electron population to be heated, while the ions remain close to room temperature.

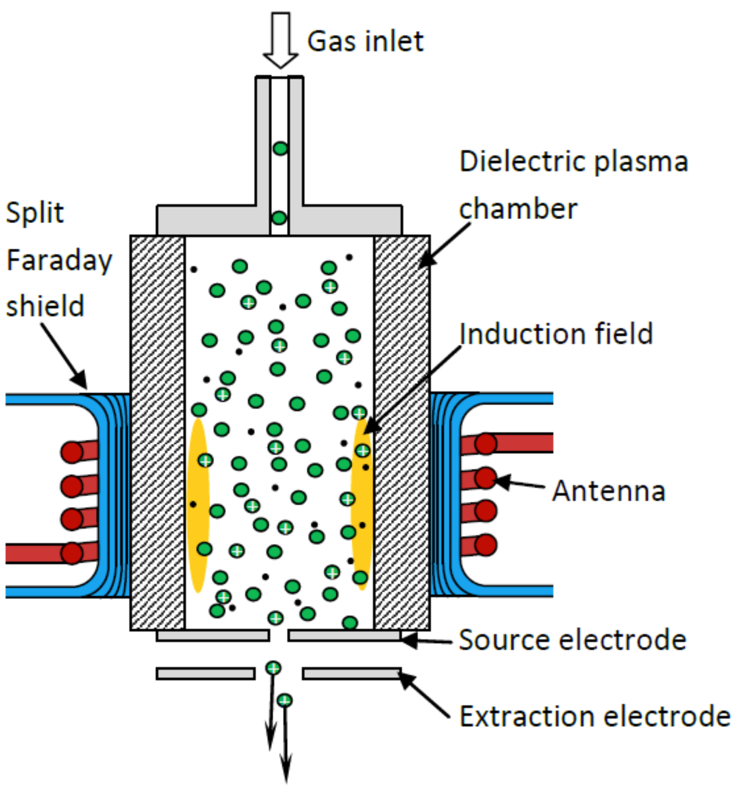

Figure 1: ICP Source Schematic

The Faraday shield has a multitude of longitudinal cuts, designed to minimize Eddy currents and power loss in the shield, while serving to terminate the time-varying electric field created by the voltage that exists on the antenna. Hence, the arrangement minimizes capacitive coupling from the antenna to the plasma, while maximizing inductive power coupling.

The induction field accelerates electrons in the outer ‘skin’ of the plasma, to a sufficient kinetic energy to cause ionization of the resident gas.

This process of creating a plasma can be used for a broad range of plasma gases and has proven able to create plasma densities as high as $1x10^{13}$ cm^{-3} (Xe^+) and resulting in a reduced brightness for the ion source of $1x10^4$ $Am^{-2}sr^{-1}V^{-1}$ [1,2].

The source can operate continuously (provided the gas supply is maintained) due to negligible aging effects in the plasma chamber, providing beam current stability of less than ±0.5 % h^{-1}, an axial energy spread of 5 eV (Xe^+) and lifetimes in excess of 2 years.

Applications:

Today, ICP oxygen (O_2^+ or O^-) beams are employed for various secondary ion mass spectrometry (SIMS) applications.

Ultra low beam energy (100 eV) ICP O_2^+ focused ion beams have replaced duoplasmatrons to provide more than an order of magnitude increase in current density in the focused beam. This enhanced level of performance results in sub-nm depth resolution SIMS depth profiling of electropositive dopant species used in the semiconductor industry[3].

For many SIMS applications, negatively charged oxygen ions (O^-) are preferred [4]. The significantly enhanced brightness and reduced energy spread of the ICP source, when compared to the duoplasmatron, has recently reduced the minimum O^- spot size from 200 nm to 50 nm, with 1pA at 15 keV.

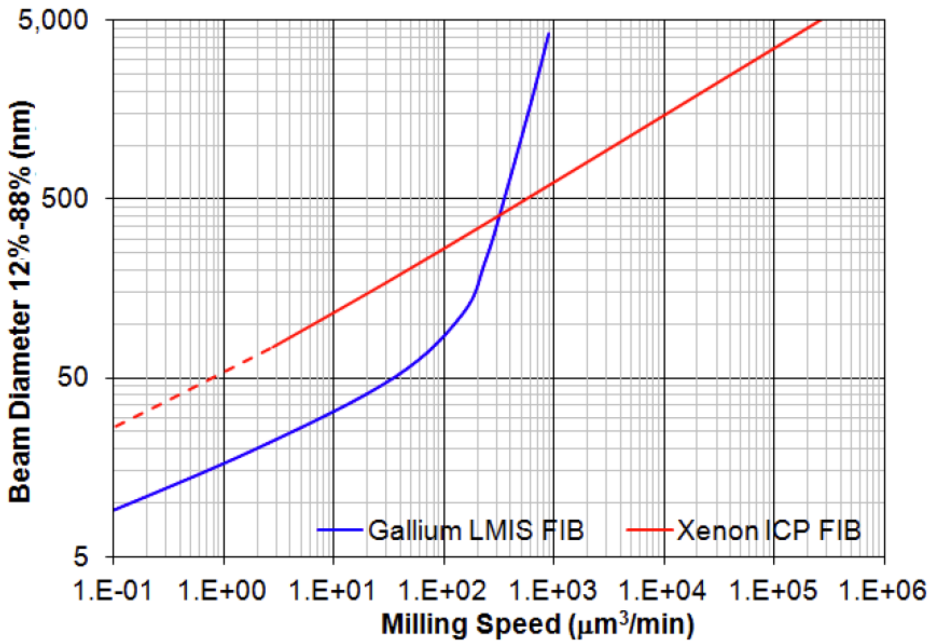

Figure 2: Spot diameter versus milling speed, for sputtering silicon at normal incidence

ICP's are commonly used to create inert gas ions, such as helium, neon, argon and xenon. These inert gas ion sources are now being used in conjunction with low energy ion scattering (LEIS) spectrometers to deliver helium, neon and argon beams with sub 5 um spatial resolution with greater than 1 nA, at 3 keV to8 keV beam energies (personal communication, J. Druce, Kyushu University).

For large volume ion beam machining, ICP produced xenon ions offer the highest sputter yields and the highest current density. Figure 2 shows optimum spot size as a function of mill rate, comparing LMIS (Ga^+) and ICP (Xe^+) 30 keV focused beams sputtering a silicon substrate at normal beam incidence. At Ga^+ beam currents above 6 nA (100 μm^3/min in **Figure 2**), the effective beam brightness (measured at the target) drops precipitously due to the relatively low angular intensity (≈15 µA/sr) of the gallium LMIS, compared to that of the ICP source (approximately≈10 mA/sr).

Present applications for the higher milling speed provided by the xenon ICP FIB, include failure analysis of bonded wafers, Through Silicon Vias (TSV's) and MEMS devices.

Status and prospects for ICP ion source performance:

Table 1 shows the reduced brightness and energy spread for common ion beam species used today.

Ion Species	β_r ($Am^{-2}sr^{-1}V^{-1}$)	ΔE_{FWHM} (eV)
Xe^+	$1x10^4$	5
O_2^+	$4x10^3$	5
O^-	$4x10^2$	3.5
He^+	$6x10^3$	5

Table 1: Source parameters for today's commercially available ICP sources.

The critical plasma parameters that determine the source brightness are the plasma density and the thermal ion energy distribution, according to **Equation 1**, where n_i is the plasma ion density and $E_\perp$ is the mean thermal ion energy.

$$\beta_r \propto {n_i}/{E_\perp} \quad (1)$$

Hence, the challenge is to maximize n_i, while minimizing the heating of plasma ions. Today's ICP's are now achieving xenon plasma densities of up to $1x10^{13}$ cm^{-3} and mean thermal ion energies of ≈0.05 eV, but it's clear that this is not the upper limit to the attainable performance. Pulsed power experiments have shown that the density can be increased by a factor of 10 and continuous power operation is now being pursued. However, it remains to be seen if $E_\perp$ will begin to increase at higher plasma densities, due to phenomena such as RF heating, electron collision heating and scattering in the plasma sheath.

Today, the energy spread for positive ion extraction is nominally 5 eV for most ion species. This net energy distribution is due to ions being created at various locations along a field gradient within the plasma (i.e. the plasma *pre-sheath*), coupled with a temporal modulation of the of the plasma potential that is synchronous with the RF waveform. By sampling the ion energy spread at a fixed RF phase angle, the temporal modulation can be eliminated from the measured energy spread. Using this measurement method, it has been determined at Oregon Physics that temporal modulations are contributing at least 2 eV to the net 5 eV energy distribution. If this temporal modulation of the plasma potential can be eliminated, an energy spread of less than 3 eV is expected.

Advancements in ICP performance will continue to be seen in the coming years, with the possibility of achieving <10 nm beam diameters with oxygen, helium and xenon ions. Today, if a FIB milling experiment can tolerate a spot size of greater than 400 nm, then the ICP Xe^+ FIB can provide greater milling speeds than the LMIS Ga^+ FIB. However, if the Xe^+ ICP brightness could be increased to $2x10^5$ $Am^{-2}sr^{-1}V^{-1}$ and the energy spread reduced to 2.5 eV, then this source will provide FIB milling speed v's resolution that's equivalent to the Ga^+ FIB at beam currents less than 6 nA, but also able to provide several microamp beams focused into a sub-micron spot.

Gas Field Ionization Source

Theory of Operation:

The underlying principle of the gas field ionization (GFIS) source is simple: a sufficiently large electric field can rip an electron from a neutral gas atom, leaving it as a positive ion. This process, field ionization, is explained quantum mechanically as the tunneling of an electron out of a neutral atom under the influence of a large electric field. For the helium atom, the ionization probability becomes appreciable when the electric field strength approaches 44 V/nm [5]. Such extremely large electric fields can be attained near the apex of a pointed needle that has been biased positively relative to a nearby extraction electrode. If the needle is sufficiently sharp (say 100 nm radius of curvature), then only a modest voltage (say +20 kV) is needed to create the required electric field. When a small quantity of gas is admitted to this region, the field ionization process can proceed, and ions are created at a typical rate of about 10^8 s^{-1}. Each newly created ion finds itself in a very strong electric field and is quickly accelerated away from the needle and towards the extractor electrode. For the purpose of visualization the emission pattern can be observed by introducing a scintillator after the extraction (**Figure 3**).

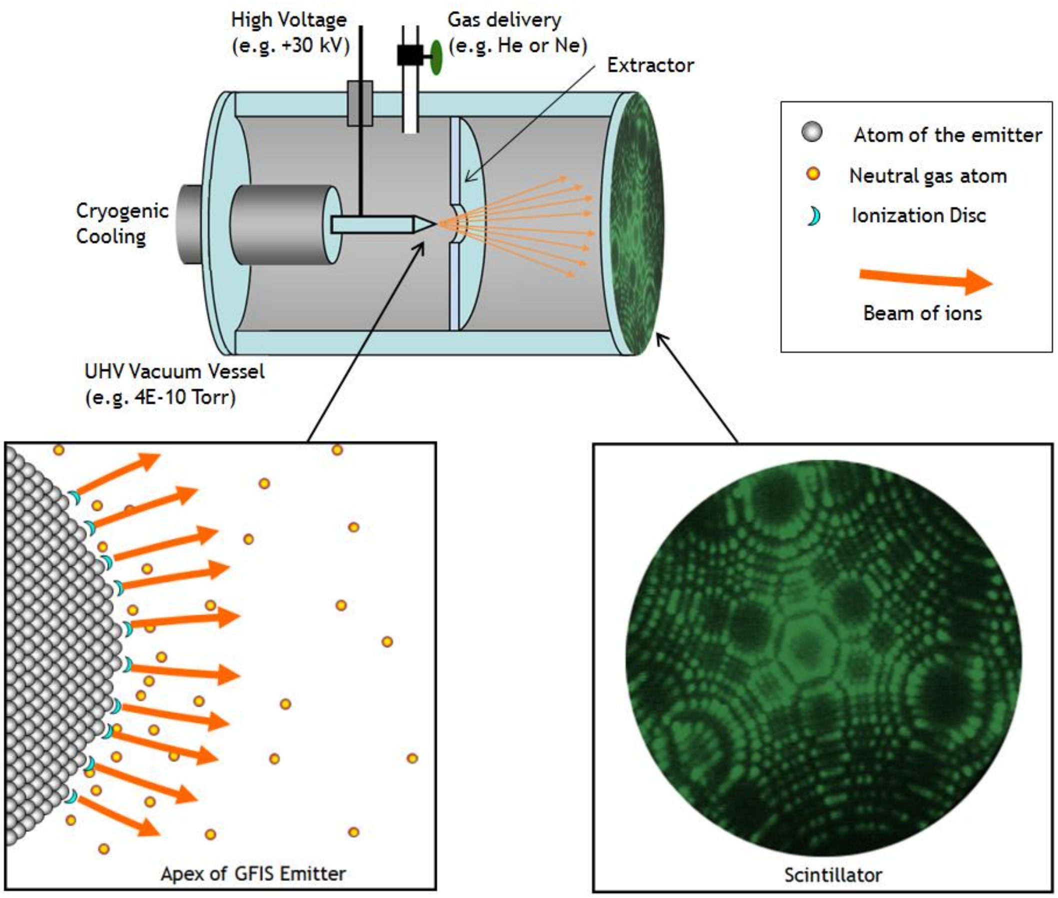

Figure 3: The Gas Field Ion Source produces an ion emission pattern that corresponds to the atomic arrangement at the apex of the emitter. Each of the most protruding atoms generates a steady beam of helium ions.

Commercialization:

As simple as this concept seems, it was not commercialized as an ion source until 2005, fifty years after its first experimental observation[6,7]. Some of the key advances were the control of the emitter shape and the precise control of the applied voltage so that only a very small volume experiences the necessary electric field strength. Under the right conditions, the necessary electric field exists solely in disc shaped volumes above the most protruding three atoms (the “trimer”) on the emitter. These ionization discs are estimated to be just a few cubic angstroms in volume, yet produce ions at rate of about 10^8 per second - a combination that is critical to producing a beam of high brightness. The small ionization volume also means that all the ions are created at nearly the same electrostatic potential thereby, producing a beam with a narrow energy distribution. Other key enabling features are the ability to maintain atomic arrangement of the emitter for the long periods of time needed for a stable ion beam. These requirements are achieved by a combination of cryogenic cooling, ultra-high vacuum, and ultra-high gas purity.

Performance Characteristics:

The characteristics of the gas field ion source are well suited to producing extremely small focused probe sizes. The reduced brightness is measured to be about 10^9 A m^{-2} sr^{-1} V^{-1} , with a 30 kV extraction voltage[8]. This remarkably high value is attributed mostly to the very small region from which the ions are produced. We estimate the energy spread of the GFIS beam to be about 1 eV full width half max (FWHM), small enough to limit the potential issues of chromatic aberration. And like most ion beams, the diffraction effects contribute only a small amount to the overall focused probe size. For these reasons, a relatively simple column consisting of two electrostatic lenses and deflectors allows the GFIS to produce a focused probe size as a small as 0.35 nm[9]. Such a small beam is well suited to high resolution imaging and fabrication at the nanometer scale. The total emitted current however is limited; the total emission current from the trimer is typically just 100 pA, and only a small portion of one emission site is selected with an aperture, typically allowing less than 5 pA to reach the sample. To achieve the highest resolution cited above, the probe current must be limited to 0.5 pA or less[9].

Clearly this technology is not suited to milling tasks requiring high removal rates; it is better suited to applications where the smallest probe size is required such as imaging and nanofabrication. The available species for the GFIS technique ion beam is somewhat limited. At present, helium is well established for imaging samples with high contrast and surface specificity as shown in **Figure 4**. A new instrument with additional neon capability is also available and affords high sputter rates for nanofabrication[10]. Other gas species, however, are not well suited to the GFIS technology because they compromise the emission stability through either chemical attack or condensation at the required cryogenic temperatures.

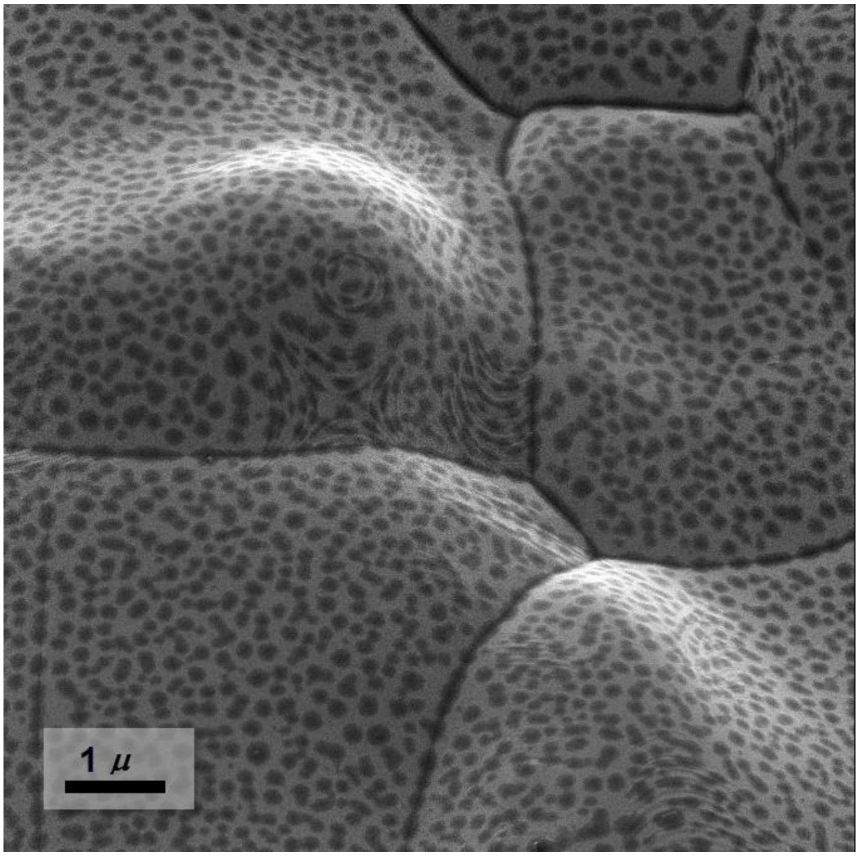

Figure 4: Chemical vapor deposited nickel after annealing, as imaged with the helium ion microscope using the GFIS technology. The mottled appearance of the surface likely arises from the rejection of solute during the annealing stage. (Sample courtesy of Fibics, Incorporated, Ottawa, Canada.)[1]

Low Temperature IonSource

Recently, a new ion source has been developed that generates a Cs^+ beam by the photoionization of laser-cooled[11] gaseous cesium. This source is referred to herein as a Low-Temperature Ion Sources (LoTIS). The development of LoTIS built upon other conceptually similar systems that also employed laser-cooling[12, 13]. In this section a theory of LoTIS operation will be presented, as will an overview of a prototype system constructed to date. The Cs^+ LoTIS has the potential to improve performance in FIB nanomachining and SIMS applications in particular.

[1] Commercial materials are identified in this paper are not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials identified are necessarily the best available for the purpose.

Theory of Operation

In a LoTIS, gaseous atoms are photoionized by photons from one or more laser beams and then accelerated by an applied electric field to form an ion beam. A schematic of the basic LoTIS concept is shown in **Figure 5**. Once a beam is formed, electrostatic deflectors and lenses may be used to focus it onto a target in a similar fashion to any other FIB system. In this section, the requirements for achieving high performance will be reviewed.

Unlike the ICP and GFIS, LoTIS-based systems have yet to be deployed to end-users as part of a complete FIB tool. Therefore, an evaluation of their potential has to date relied on measurements performed on the ion source itself; knowledge of LoTIS (normalized) brightness and chromatic energy spread enables projections of anticipated focal spot sizes at any given current and beam energy. The fundamental equation for brightness in a LoTIS is[14]:

$$B = \frac{J}{\pi k_B T} \tag{2}$$

where J is the cross sectional current density of the ion beam generated by the source and T is the temperature of the ions along the directions transverse to the beam. It is helpful to consider the simplest implementation of such a system to get a sense of the values for J and T required to achieve source brightness significantly larger than that of the LMIS value of 10^6 $\mathrm{Am^{-2}sr^{-1}V^{-1}}$. The current density J will be determined by the density of neutral atoms and the efficiency of the laser in ionizing them.

Consider a simplified system where atoms at given pressure are all ionized if they pass through thin sheet of laser light. A simple estimate of J in this case can be written (15):

$$J = \frac{\sqrt{2}eP}{\sqrt{\pi m k_B T}}, \tag{3}$$

where P is the pressure of the gas, and m the atomic mass. For a pressure of 7×10^{-4} Pa (5×10^{-6} Torr) at room temperature this implies a brightness of less than 40 $\mathrm{Am^{-2}sr^{-1}V^{-1}}$, many orders worse than the LMIS. High brightness operation therefore requires either a large increase in current density or a large reduction in temperature. Laser cooling enables the dramatic reduction in temperature required to achieve high brightness. The key idea that enables this is that if the photo ionization lasers are properly tuned near the threshold for ionization then the velocity distribution of the ions they create will be nearly identical to that of the neutral atoms.

In the Cs^+ LoTIS, atoms are first captured from a low pressure background vapor and formed into a high-flux atomic beam and then compressed using magneto-optical trapping. The beam is then cooled using an optical molasses[11] and then finally photoionized. These techniques allow for the creation of a cold, dense (above $10^{17}\,\mathrm{m^{-3}}$) atomic ensemble while maintaining background pressures below 10^{-6} Pa (10^{-8} Torr) in the part of the source where ions are created. Recently, a system was demonstrated[16] with a $J = 0.16$ Am^{-2} and $T = 30$ μK, giving rise to a Cs^+ source with a brightness greater than 10^7 Am^{-2}sr^{-1}V^{-1}.

Not all atomic species are usable with LoTIS because not all are amenable to laser cooling; the alkalis may all be cooled, as may the noble gases and several other metals such as chromium and erbium. Reductions in temperature to below $100\ \mu$K are achievable with a few of these atomic species. However, switching between atoms in the same system presents 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 LMIS.

The effects of Coulomb interactions are an important consideration in a LoTIS; these interactions will broaden the ion velocity distributions along the directions transverse to the beam, leading to an effective increase in temperature. Because LoTIS has a lower current density at its origin than point emitters such as the LMIS or GFIS, maintaining a low temperature is vital to maintaining high brightness. It was shown however[16-18], that with a high enough electric field (10^5Vm^{-1} or greater), quickly accelerating the ions away from the source as they are created, this heating will be small enough so as to not substantially impact performance, especially in the lower current modes of operation.

The LoTIS has a smaller energy spread than most other ion sources and this contributes to enhanced performance, especially at lower beam energies and beam currents. As in other focused ion beam systems employing electrostatic lenses, chromatic aberrations must be minimized in order to achieve an optimal focal spot size; these aberrations are proportional to the spread in energies in the ion beam. In a LoTIS, the energy spread is equal to the electric field used to accelerate the ions multiplied by the physical extent of the source along the direction of the field. This size is determined by the size of the ionizing laser(s), typically focused to a couple microns. With an electric field of order 10^5Vm^{-1} this implies an energy spread of a few tenths of an eV, substantially better than the LMIS and similar to the GFIS.

LoTIS developments to date

LoTIS-based systems have not been deployed in commercial devices yet. Predecessor ion source technology that also employed laser-cooling has been incorporated into focused beam prototypes of lithium[12] and chromium[19]. The lithium system fully integrates a laser-cooling based ion source with a commercial FIB platform from which the LMIS was removed. These test systems demonstrate the feasibility of LoTIS/FIB integration.

The most recent LoTIS development work[16] shows that these sources can produce Cs^+ beams with a brightness greater than 10^7 Am^{-2}sr^{-1}V^{-1} with an energy spread below 0.4 eV. One reason cesium was chosen for that work is because it is the heaviest of the easily laser-coolable atomic species. When fully integrated into a FIB tool such a system would have numerous advantages. Sub-nm focal spots at 1 pA beam current with a heavy ion would enable nanomachining processes on the finest scales combined with potentially reduced sub-surface contamination and damage than would occur with a lighter ion. The system's low energy spread means it should offer enhanced performance at lower beam energies, when compared with other ion sources. It should offer great flexibility as well. With the capability to output beams with a current of several nA, albeit at reduced brightness, the Cs^+ LoTIS will be able to address both fine and medium-scale milling tasks. Additionally, the use of cesium suggests the possibility for development of a tool that can perform secondary ion mass-spectrometry tasks as well. The potential of LoTIS-based FIBs may be realized subsequent to further development.

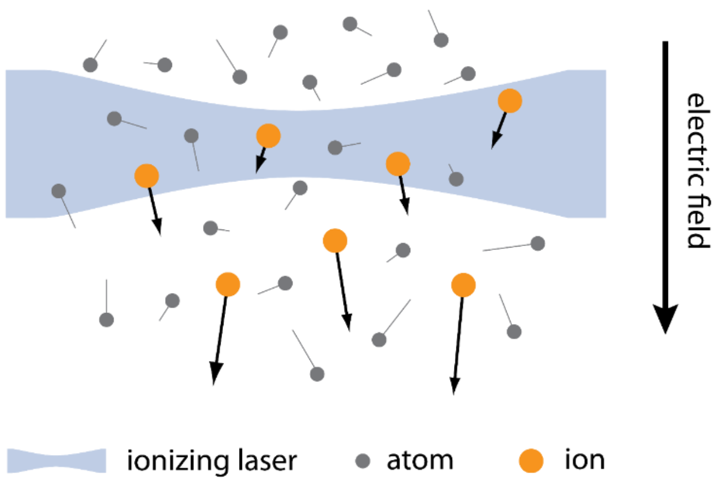

Figure 5. In a low-temperature ion source gaseous atoms are photoionized from a cold, dense atomic ensemble prepared through the techniques of laser-cooling.

Summary

The ion source technologies presented here extend the capabilities of the conventional gallium LMIS in one aspect or the other. These improvements include higher brightness, lower energy spread, and the ability to operate with alternative ion species - or some combination of these. When employed in a FIB system, these new ion sources can extend its usefulness to new applications, or improve upon the performance of the more well-established ones; it is these advantages relative to the gallium LMIS, that we anticipate will bring about their commercial acceptance in specific applications.

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Figure Captions

Figure 1: ICP source schematic

Figure 2: Spot diameter v's milling speed, while sputtering at normal incidence on silicon

Figure 3: The Gas Field Ion Source produces an ion emission pattern that corresponds to the atomic arrangement at the apex of the emitter. Under the proper conditions, each of the most protruding atoms generates a steady beam of helium ions.

Figure 4: Chemical vapor deposited nickel after annealing, as imaged with the helium ion microscope using the GFIS technology. The mottled appearance of the surface likely arises from the rejection of solute during the annealing stage. (Sample courtesy of Fibics, Incorporated, Ottawa, Canada.)

Figure 5. In a low-temperature ion source gaseous atoms are photoionized from a cold, dense atomic ensemble prepared through the techniques of laser-cooling.

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Noel Smith is a co-founder and scientist at Oregon Physics LLC. Noel received his Ph.D. in physics from Warwick University in the U.K., where he developed a low energy focused ion beam for high depth resolution SIMS analysis. Noel has developed ion/electron optics and ion sources for a number of FIB and surface science instrument development companies, before co-founding Oregon Physics in 2007. Today, Noel is focusing on the further development of ion sources and probe forming optics. Noel can be reached at n.smith@oregon-physics.com.

Adam V. Steele is a co-founder of zeroK Nanotech Corporation, a startup focused on the commercialization of high-brightness ion sources that utilize laser-cooling. Adam received his Ph.D. in physics from The Georgia Institute of Technology where he researched the laser-cooling of ions with application to nuclear clocks and quantum information processing. Prior to founding zeroK Adam worked at the National Institute of Standards and Technology on a proof-of-concept retrofit of a Low-Temperature Ion source with a commercial focused ion beam system. Adam can be reached at adam@zerok.com.