A High Brightness Source for Nano-Probe Secondary Ion Mass Spectrometry

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Abstract

The two most prevalent ion source technologies in the field of surface analysis and surface machining are the Duoplasmatron and the liquid-metal ion source (LMIS). There have been many efforts in this area of research to develop an alternative source [1,2] with the brightness of a LMIS and yet the ability to produce secondary ion yield enhancing species such as oxygen. However, to date a viable alternative has not been realized.

The high brightness and small virtual source size of the LMIS are advantageous for forming high resolution probes but a significant disadvantage when beam currents in excess of 100nA are required, due to the effects of spherical aberration from the optical column. At these higher currents a source with a high angular intensity is optimal and in fact the relatively moderate brightness of today's plasma ion sources prevail in this operating regime. Both the LMIS and Duoplasmatron suffer from a large axial energy spread resulting in further limitations when forming focused beams at the chromatic limit where the figure-of-merit is inversely proportionally to the square of the energy spread. Also, both of these ion sources operate with a very limited range of ion species.

This article reviews some of the latest developments and some future potential in this area of instrument development. Here we present an approach to source development that could lead to oxygen ion beam SIMS imaging with 10nm resolution, using a 'broad area' RF gas phase ion source.

Introduction

Since the 1960's the cold cathode Duoplasmatron has been the most commonly used source for oxygen ion generation in the field of Secondary Ion Mass Spectrometry (SIMS). First invented by von Ardenne [3] and later adopted for SIMS applications [4], the source has been refined to a level of performance reported by Coathe and Long [5] for argon and oxygen operation. Various groups have used the source with reactive gases such as SF_6, and suffered with poor lifetime and beam stability. The source has also been long employed outside the SIMS community for proton generation and is still the source of choice at CERN in the search for the Higgs particle [6].

The Coathe and Long Duoplasmatron has a maximum reduced brightness (β_r) of 1100 $Am^{-2}sr^{-1}V^{-1}$ with argon, while commercially available sources typically operate at 250-500 $Am^{-2}sr^{-1}V^{-1}$ for Ar^+ and O_2^+ and 25-50 $Am^{-2}sr^{-1}V^{-1}$ for O^- production. The energy spread of this source tends to be in the range of 5-15eV and has a short and often unpredictable lifetime (~50-500 hours).

For SIMS applications requiring a lateral resolution in the nanometer scale, this source doesn't have the required performance. At high energy and low beam currents (eg 30keV and 10pA), the source of Coathe and Long can theoretically only achieve a spot size of ~85nm if one employs an ion column with typical aberration coefficients (C_s~120mm and C_c~40mm).

For these high resolution applications, the liquid metal ion source (LMIS) has been widely used since the 1970's when the blunt needle-type LMIS from Clampitt and Jefferies [7] was used by Krohn and Ringo [8] in the first reported LMIS based ion column. Generating high current density beams with sub-100nm beam diameters is now common place with the LMIS [9]. A comparison of calculated spot size (diameter containing 50% of the beam current, d_{50}) versus total beam current is shown in figure 1, for a typical oxygen Duoplasmatron (β_r=400 $Am^{-2}sr^{-1}V^{-1}$) and the gallium LMIS (β_r=1x10^6 $Am^{-2}sr^{-1}V^{-1}$), both optimally operated at 30keV with a generic 3 lens ion column. Of course, the significantly higher current density at <1nA for the LMIS results from value for $(\beta_r/\Delta E^2)$ being four decades higher than the Duoplasmatron. However, at higher currents the much larger acceptance angle required for the LMIS becomes highly problematic. At these large currents(beam acceptance angles), the optical column is required to operate in a mode that has close to unity optical magnification and gun lens spherical aberrations dominate causing the LMIS spot size to increase proportionately to the 3rd order geometric lens aberrations [10]. At these higher beam currents, often required for dynamic SIMS applications, a high brightness point source does not suffice and in fact a high angular intensity is required, even at the expense of overall brightness and energy spread.

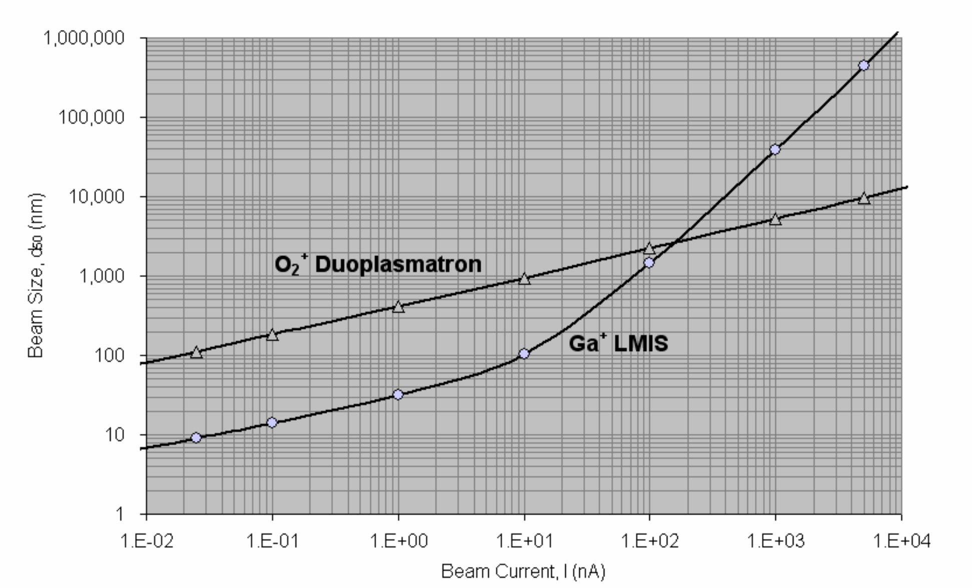

Figure 1. O_2^+ Duoplasmatron, β_r=400Am^{-2}sr^{-1}V^{-1}, ΔE=10eV compared to Ga$^+$ LMIS, β_r=1x10^6 Am^{-2}sr^{-1}V^{-1}, ΔE=5eV.

Of course, the electropositive secondary ion yield is much lower when using a gallium beam, resulting in the detection limit of some sample species being 2 orders of magnitude lower than achieved with an oxygen beam. Hence, sub-100nm beam diameters with a yield enhancing oxygen beam would be greatly beneficial for compositional analysis of nano-particles and individual device structures for the semiconductor and MEMS industries.

In recent years, various researchers have developed plasma ion source technology for various high current applications. This work has been largely led by the high energy physics community, as well as those who develop plasmas for wafer processing and ion thrusters [11,12,13]. Several of these sources have been studied and developed for ion beam applications such as SIMS and FIB machining.

Notably, the ‘Multi-Cusp’ ion source has undergone a significant amount of study and development at Lawrence Berkeley Laboratories (LBL) [14,15] for applications including neutron generation, wafer processing and focused ion beams. Here the magnetic field cusps formed at the perimeter of the plasma reduce radial electron diffusion to the walls while the bulk of the plasma is field free with a uniform plasma density across the majority of its cross-section. This approach has been very successful for wafer processing where areal dose uniformity is critical, however the maximum source brightness reported by Scipioni *et al* [16] of 550 Am^{-2}sr^{-1}V^{-1} is only comparable with the Duoplasmatron. The main attraction of this source is the reported 1eV axial energy spread [17], which at low beam currents is a significant advantage and could result in a beam diameter as small 60nm at 10pA, but inferior performance to the Duoplasmatron at high beam currents due to the dominance of spherical aberration from the focusing optics.

Guharay *et al* have advanced the development of the Penning ion source primarily for negative hydrogen and oxygen extraction, but also for positive argon ions. With argon a maximum reduced brightness of 10^3 Am^{-2}sr^{-1}V^{-1} with ΔE=4.5eV has been achieved [18], while with H$^-$ a pulsed (1% duty factor) brightness of 7x10^4 Am^{-2}sr^{-1}V^{-1} and an energy spread of 3eV were possible, however, the time averaged reduced brightness is still only 700 $Am^{-2}sr^{-1}V^{-1}$. For O^-, Guharay reports a factor of 4 reduction in brightness over H^- [19], resulting in a time averaged brightness of only 175 $Am^{-2}sr^{-1}V^{-1}$. This performance with O^- is factor of 3-5 higher than typical Duoplasmatrons and for pulsed applications, the Penning source could be an interesting option. One significant problem with this and any such DC plasma source is the practical lifetime limitations that are further exacerbated when reactive and high molecular weight gases are used.

For high current milling applications that require either inert, reactive or cluster ion species, RF based ion sources seem to be leading the field in terms of brightness and have the potential for significant further improvements. Since these sources operate without a cathode, there can be little-to-no sputtering inside the source allowing them to operate at very high power densities and still maintain a good lifetime even with reactive species.

Radio Frequency Plasma Ion Sources

RF plasmas have been around since Hittorf reportedly produced the first plasma by induction, using a coil surrounding a dielectric tube back in 1884 [20]. However, this branch of AC plasma ion sources has been slow to evolve into the mainstream for focusing ion column optics.

For this type of plasma generation, RF power can be coupled to the plasma inductively, by either immersing an antenna into the plasma or more commonly positioning a helical antenna around the circumference of a cylindrical dielectric plasma chamber. The RF current flowing through the antenna induces as RF magnetic field (***B***) which penetrates through the dielectric chamber. Following Faraday's law of induction ($\nabla \times \boldsymbol{E} = -\partial \boldsymbol{B}/\partial t$), the time-varying RF magnetic field induces an azimuthal electric field (***E***). The induction field induces an electron current in the skin of the plasma, generating sufficiently energetic electrons to cause ionization of the resident gas molecules.

Leung *et al (*Lawrence Berkeley Labs, LBL) have demonstrated and described various inductively coupled plasma (ICP) sources using helical coil antennas and there applicability to focusing ion column optics. The highest performance reported by LBL [21] resulted in an Ar^+ current density of 220 mA/cm^2 from the source and it was concluded by extrapolation from the current density and associated brightness of the multi-cusp source characterized by Scipioni, that this source would have a reduced brightness of ~$2.3x10^4$ $Am^{-2}sr^{-1}V^{-1}$. Unfortunately, no experimentally derived brightness values have been reported by this group. Similar results are reported by Mordyk *et al* [22] who determined by microwave interferometry that the plasma density at the source aperture is $7.2x10^{12}$ cm^{-3} for argon which would also equate to a current density of ~200mA/cm^2 if one assumes a mean electron temperature (T_e) in the plasma of 3-4eV. Mordyk asserts that this source is coupling energy to the plasma via Helicon waves as opposed to the inductive coupling of the Leung source, but both report similar performance and surmise that a reduced brightness of the order of 10^4 $Am^{-2}sr^{-1}$ V^{-1} can be anticipated.

However, another recent report by Smith *et al* [2] *(this author)* also describes an RF driven ion source that couples energy inductively to the plasma and employs a form of magnetic plasma confinement. Here, an argon plasma yielded a current density of ~76mA/cm^2 and the measured source brightness was determined to be 5400 $Am^{-2}sr^{-1}V^{-1}$, while with Xenon a brightness 9100$Am^{-2}sr^{-1}V^{-1}$ was measured. The higher Xenon brightness was due to the higher plasma density for a given RF power, with the thermal ion energy being the same for both gases. Hence, by simple extrapolation the source of Jiang might be expected to have a reduced brightness approaching $2x10^4$ $Am^{-2}sr^{-1}V^{-1}$ as predicted, but only if we assume that the thermal ion energy of the plasma ions and the emittance growth from the extraction optics are comparable. It's plausible that the Mordyk source may be more prone to greater ion heating via the Helicon wave interaction, however this is not the case with the LBL source or other such inductive ion sources.

For the SIMS analysis of electropositive materials, the question remains how well would this type of source perform with oxygen and what is the future potential for an RF generated oxygen plasma. Although the source reported by Smith has an energy spread that is comparable to a Duoplasmatron when running argon, it is also pointed out that the RF source may not be fundamentally limited to this value and there is a chance that the theoretical limit of ~1.5eV is plausible if the plasma modulation could be eliminated.

Results from a Configurable Plasma Ion Source

A configurable plasma source has been built and is now being studied at Oregon Physics that is capable of being operated with or without multi-cusp field confinement, helicon wave coupling or inductive field coupling as well as other novel modes of operation. Initial results from this source have been acquired while operating in the most rudimentary of RF configurations, with an external RF antenna and no confinement field. Figure 2 shows initial emission current data from this source configuration, with the extracted current increasing in the typical manner with extraction potential for 500W of RF power. The extraction optics and first condenser lens have been designed to operate with an extraction potential of nominally 12kV. With this extraction field a beam current of 28.5μA is accelerated from a 175μm anode aperture, providing a nominal current density of 118mA/cm^2.

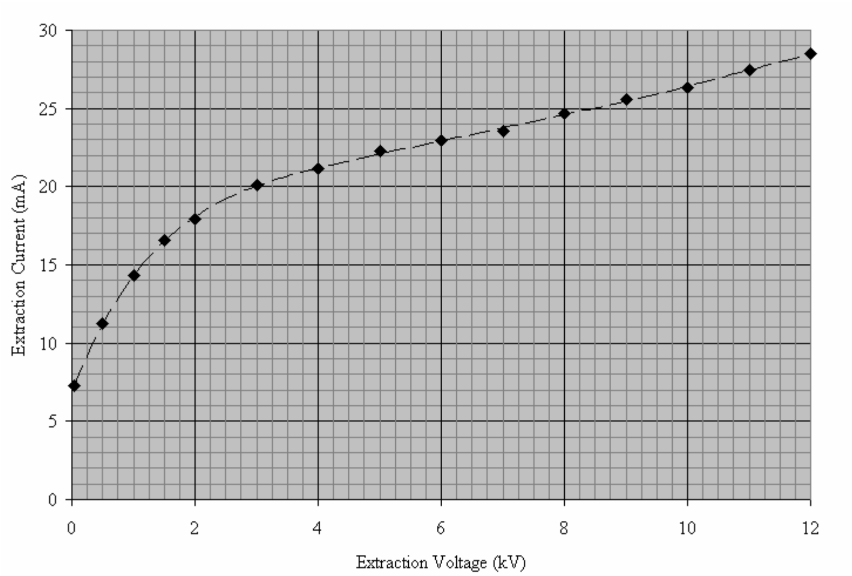

Figure 2. Current Density as a function of extraction voltage.

Figure 2 shows the classical diode-like behaviour of a plasma ion source, with a sharp 'switch-on' at low acceleration potential. Space charge effects, charge exchange and losses to the anode aperture walls rapidly abate as the curvature of the convex plasma meniscus is reduced with increasing extraction voltage. Above 4kV the plasma meniscus is believed to be concave, with the gradual increase in current being attributable to an increase in surface area of the ion emissive region. If one assumes that the emissive surface is flat at an extraction potential of 3kV and the ion current of 20μA hasn't suffered any losses from charge exchange beyond the plasma sheath and no losses to the anode aperture walls, then we can assert that the plasma density at the exit to the source is approximately 6x10^{12} cm^{-3} according to equation (1). Here, n_i is the plasma density, I_{ext} is the extracted ion current, q is the fundamental charge on an electron, r_{ap} is the anode aperture radius, k_b is Boltzmann's constant, T_e is the mean electron temperature in the plasma and M_{Xe} is the mass of a Xenon ion, all in S.I. units.

$$n_i = \frac{I_{ext}}{0.6\pi q\, r_{ap}^{\,2}\sqrt{k_B T_e / M_{Xe}}} \qquad (1)$$

This source has been attached to a three lens ion column, with a neutral filter immediately below the source, a variable angle defining aperture, nominal image side C_c and C_s values of 55mm and

205mm respectively for the objective lens and a variable beam energy of 0-30keV. Spot size (d_{50}) versus beam current for this source and column operating with Xenon are shown in figure 3. Back calculation of the reduced source brightness gives a value of 1.3×10^4 $Am^{-2}sr^{-1}V^{-1}$, indicating a mean thermal ion energy ($E_{thermal}$) of only 0.04eV according to equation (2). In equation (2), the value $\sqrt{2}$ accounts for the entire phase space of the beam rather than just the d_{50} virtual source size. β_r is determined by evaluating the virtual source location, the virtual source diameter and the angular intensity under fixed source and extraction operating conditions. With the anode potential at 15kV, the extractor at 3kV, lens 1 and lens 2 at 0V, the Gaussian beam diameter is determined at the target using only lens 3 to focus. The same measurement was then done with lens 1 and 3 at 0V, while lens 2 is used to focus the beam at the target. Knowing the Gaussian spot size under these two operating conditions (deconvolving lens aberrations if necessary), the distance between the principle planes of lens 2 and 3, and the distance from the lens 3 principle plane to the target is sufficient information to determine the virtual source location. In this work, the virtual source was determine to be only 2mm behind the anode aperture, with a virtual source size, d_v~13µm and an angular intensity, I' ~ 27mA/sr . The calculated value for β_r is the practical reduced brightness, determined 'looking back' from the beam acceptance aperture to the 1st lens. Hence the value includes aberrations from the extraction optics as well as global and stochastic space charge effects, resulting in an over-estimate of the mean thermal energy of the plasma ions.

$$E_{thermal} = \frac{I_{ext}\sqrt{2}}{\pi^2 \beta_r \, r_{ap}{}^2} \qquad (2)$$

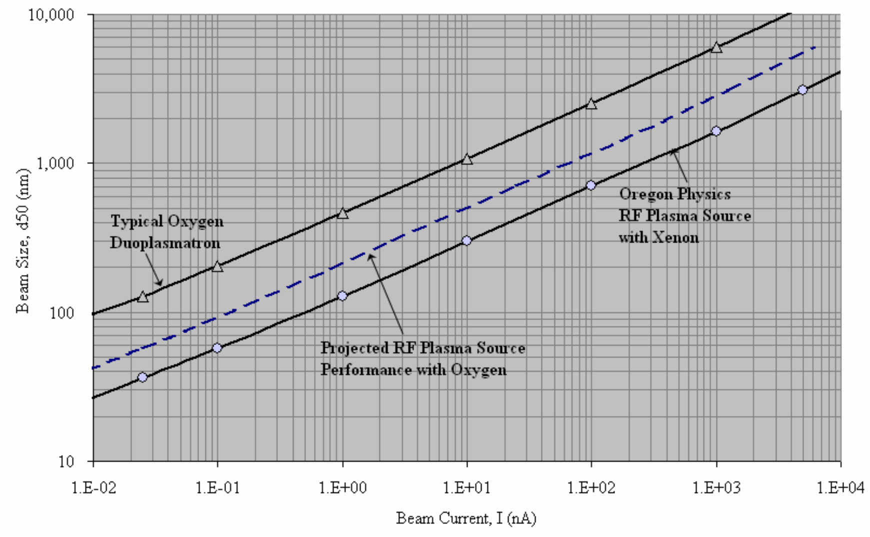

Figure 3. Beam diameter (d_{50}) as a function of beam current at 30keV.

Although the source is not providing an unusually high current density for a plasma ion source, the source brightness is relatively high by virtue of the apparent mean ion temperature being only 150-200^{0}C above room temperature.

The next step is to determine the source brightness with oxygen. Oxygen has a lower cross-section for ionization than xenon and we anticipate a current density that is approximately a factor of 4 lower, resulting in β_r ~ 3250 $Am^{-2}sr^{-1}V^{-1}$. This brightness is a factor of 8-10 higher than typical Duoplasmatrons. With an energy spread of 5eV the enhanced source brightness will result in a 10pA, 30keV beam size of 42nm and at 1pA, 22nm is possible. If the energy spread could be lowered to the proposed theoretical limit of 1.5eV, then we could anticipate the d_{50} beam size dropping to 16nm for 1pA.

Conclusion

A high brightness, plasma source has been built and initial performance data indicates high resolution SIMS imaging will be possible. With our present optical column, we anticipate oxygen ion beam spot sizes as low as 21nm at 30keV (ΔE=5eV). However, at the extremely short working distances of the NanoSIM50 one would expect d_{50} beam diameters of ~20nm with 1pA and 15keV beam energy, and if the energy spread can be reduced to the theoretical limit, 15nm will be possible. The enhanced brightness of this RF plasma source will provide an 8-10 times decrease in image acquisition times for a given resolution and optical system and a step increase in attainable SIMS imaging resolution.

In general, AC plasma generation can be far superior to the more commonly employed DC plasma sources. The lack of a cathodic element being sputtered in the source can result in long lifetimes and stable current and brightness over extended periods.

Research at Oregon Physics is now directed towards further developments for this type of source technology for SIMS and other surface science applications. Several novel concepts are being explored that will provide further improvements in source brightness and axial energy spread for oxygen ions, as well as other reactive ion species, inert gases and large cluster species. These further improvements promise 10nm resolution SIMS imaging in the not too distant future.

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