New Ion Probe for Next Generation FIB, SIMS, and Nano-Ion Implantation

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Introduction

Hyperion™ is a newly developed high-performance ion source that significantly advances the capabilities of many ion beam techniques used by material scientists and engineers. Hyperion has been developed to provide focused beams as small as 10 nm, beam currents up to several micro-Amps, and a broad range of ion species that include He^+, O_2^+, Xe^+ and H_3^+.

This technology provides state-of-the-art performance in many areas of surface science and engineering that include FIB milling, nano implantation, and high-resolution surface analysis. This paper summarizes a few applications that have been explored with this new system, along with some of the enhanced capabilities that can be anticipated with future implementations.

Hyperion is a high-density, non-thermal plasma ion source that exhibits very high brightness, low energy spread and is able to operate reliably with inert and reactive plasma gases. [1, 2]

RF power is inductively coupled from an external antenna to the boundary electrons of the plasma. The electrons are accelerated to sufficient energy to ionize resident gas molecules, however, conditions are maintained to ensure minimal ion heating and a static plasma potential. The Hyperion plasma is remarkably quiescent, allowing us to impart a very large power density and thus create a correspondingly high plasma density without compromising source lifetime. Hyperion can operate with a broad range of inert and reactive plasma gases, forming primarily singly ionized atomic and molecular ions.

Figure 1: Hyperion plasma ion source

This new source is now providing *useable* beam current that extends to many micro-amps with an energy normalized brightness of $>1\times10^4$ $Am^{-2}sr^{-1}V^{-1}$ with xenon, 6.7×10^3 $Am^{-2}sr^{-1}$ V^{-1} with helium, 4.5×10^3 $Am^{-2}sr^{-1}V^{-1}$ with oxygen, and 2.7×10^3 $Acm^{-2}sr^{-1}$ with hydrogen. These "brightness" figures are more than an order of magnitude higher than the duoplasmatron [3], which has been the most commonly used plasma source for high-performance, plasma-based focused ion beams. Furthermore, Hyperion has an energy spread of only 5-6 eV, resulting in a figure-of-merit at the chromatic limit [10] that is approximately a factor of 50 higher than the workhorse duoplasmatron.

Additionally, Hyperion has an angular intensity that is 3 orders of magnitude higher than a liquid-metal ion source (LMIS). Compared to the LMIS FIB, this property translates to a higher effective brightness (at the target) for Hyperion FIB currents >30-40 nA at 30 keV. However, beam quality is often quite poor with the LMIS FIB, even at beam currents of 20 nA due to the dominance of third-order geometric aberrations at large aperture angles [4]. Even with a perfectly aligned optical column, the LMIS FIB spot shape exhibits an intense central spot with long tails indicative of beams dominated by spherical blur.

FIB Milling

The high brightness (1×10^6 $Am^{-2}sr^{-1}V^{-1}$), small virtual source size (50 nm), and low angular intensity (20 µA/sr) of the LMIS used in most FIB columns is advantageous for forming high-resolution probes for small-volume milling but a significant disadvantage when beam currents in excess of 20 nA are required. Although a 30 keV, gallium LMIS-FIB can form a spot size of ~200 nm with 20 nA, the beam tails will

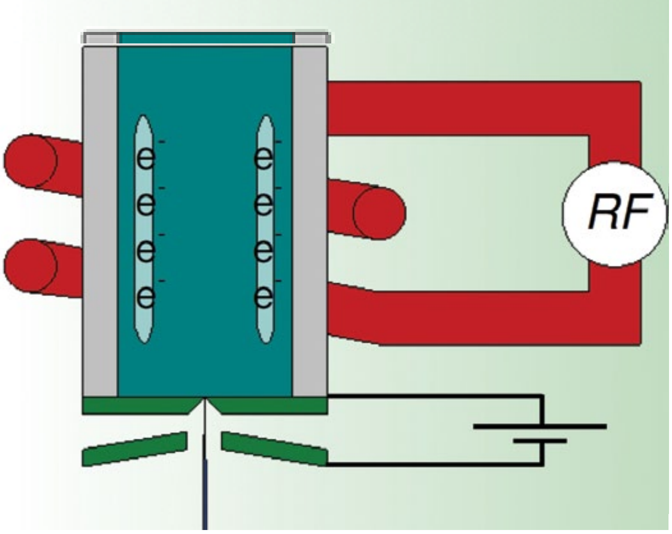

Figure 2: RF induction coupling to plasma electrons.

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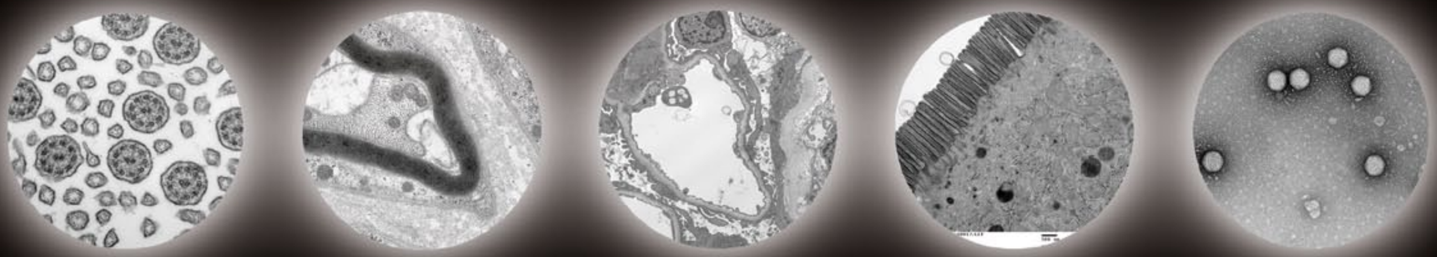

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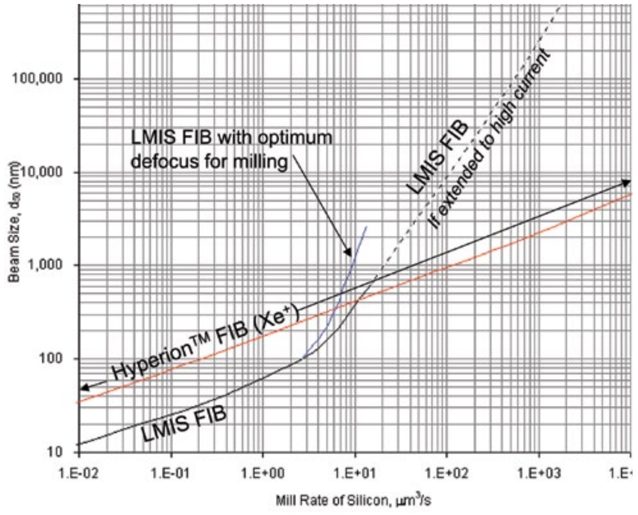

Figure 3: Beam size versus mill rate for the Hyperion FIB (red line) with LMIS FIB (blue line).

be extensive, resulting in poor edge abruptness when milling. For milling purposes, these higher current LMIS beams require some *de-focus* from the optimum image resolution to give a well-circumscribed beam profile. At 20 nA the LMIS FIB objective lens is often defocused marginally to pull in the beam tails, while increasing the d_{50} (beam diameter containing 50 percent of the current) beam width by a factor of ~1.5. At 50 nA, the milling beam would need to be defocused by almost a factor of 5 to minimize the beam tails from spherical blur.

Figure 3 compares 30keV LMIS and Hyperion performance, in terms of the optimum beam size (or milling resolution) as a function of milling rate for a silicon target. Here we use a sputter rate of 0.27 μm^3/nC for the gallium beam and 0.46 μm^3/nC for the xenon beam. For a true comparison of milling resolution, the blue line shows the beam width with the optimum defocus for the LMIS to achieve suitable milling beams. Once the enhanced sputter yield is accounted for, along with the required LMIS FIB defocus, Hyperion shows a gain in milling resolution at rates above ~6 μm^3/s, equating to a gallium beam current of 20 nA.

This precipitous drop in milling resolution for the LMIS FIB results from the large acceptance angles required for low-angular intensity ion sources. So, at these higher currents, a source with a high-angular intensity is optimal even at the expense of overall brightness. In fact, the effective beam brightness of the Hyperion source (at the target) can be maintained from pico-Amps up to many micro-Amps. Due to an angular intensity of ~10 mA/sr, Hyperion excels at beam currents >20 nA, while still having the brightness and energy spread to provide <25 nm resolution for fine milling and imaging at 30 keV.

The Hyperion FIB is now satisfying a broad array of milling applications, which includes large-area cross-sectioning of next-generation 3D IC technologies, such as "Through-Silicon Vias" (TSVs) [5]. TSV interconnects are thought to be the ultimate solution to overcome the space limitations of Package-on-Package (POP) and System-in-Package (SiP) devices. POP and SiP packages rely on standard off-chip wire bonds or solder bumps for making interconnections, whereas 3D-ICs have dramatically shortened interconnect lengths by connecting circuits with vias passing directly through the silicon wafer. The benefits of reduced interconnect dimensions include faster data transfer rates and devices requiring less power.

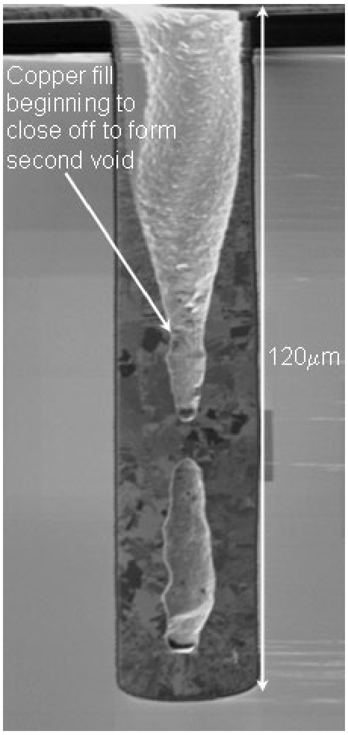

Figure 4: Deep cross-sectional analysis of a "Through Silicon Via," sectioned and imaged with Hyperion FIB.

In order to attain reliable fabrication of TSVs, cost-effective via inspection is required for process and failure analysis. The copper fill process for these vias often results in unwanted sub-micron voids forming on the via axis unless the precise electro-deposition process is found for the particular via dimensions chosen. Finding these small axial voids is best accomplished by successively removing a thin layer of material from a cross-sectioned via and then imaging the newly revealed face. Other artifacts of via manufacturing can require close examination of the via walls or interfacial regions, but in all cases precise removal of material is required. Mechanical polishing alone can result in mechanical stresses and damage to the vias. Broad-area ion beams lack the site specificity to iteratively remove material and image the site of interest, and the LMIS-FIB is too slow to remove the required material volumes that often exceed 10^6 μm^3 during an analysis. At 6 μm^3/s, a 20 nA gallium beam would be an impractical, expensive solution taking approximately 46 hours of instrument time.

However, the example shown here has been prepared with just 30 minutes of milling with the Hyperion FIB system. In this case, the via is approximately 120 µm deep and 20 µm wide with void formed at the base of the via and indications that further voids would have occurred if the copper deposition process had been completed.

In the coming years, critical interconnects and vertically stacked circuitry will often need to be excavated by deep FIB milling for failure analysis. Yole Développement estimate that over the next 3-4 years, the volume of 3D wafers fabricated will increase 10-fold. The number of TSVs per die could be as high as 10^5 with 10-15 wafers per die aligned and bonded to within ±1 µm. New materials and fabrication processes are being investigated for enhanced thermal management and optimal high-density device stacking. It is anticipated that future 3D devices will have active circuitry and interconnects in a stack of silicon of up to 1 mm high. The Hyperion FIB now provides a viable ion-beam technique to tackle this type of precision cross-sectioning.

Other applications such as prototyping MEMS and embedded circuit components have been demonstrated with this high-current FIB. Figure 5 shows a micro-scale spiral RF antenna, often used in RF ICs, that has been fabricated here in <60 minutes. A 5 µm thick layer of copper has been locally sputter deposited over a ~250x250 µm area of silicon oxide with a 3 µA Xe$^+$ beam hitting a copper target and creating a conformal deposit in ~25 minutes. A bitmap has been uploaded to the FIB pattern generator, directing a 250 nA, 25 keV Xe$^+$ beam to mill away the excess copper. The deposited copper has a measured electrical conductivity that is within a factor of 3 of bulk copper, such that this 2.5 nH (calculated) inductor would have a quality factor (Q) of ~20 at 5 GHz, ignoring substrate losses and parasitic capacitive effects that can affect these parameters at higher frequencies.

Often spiral RF inductors are developed with a combination of electromagnetic simulations and characterizing a number of prototype spirals on test wafers. However, the simulation process is far from trivial [6] at the dimensional scales used for today's compact RF ICs. The performance of a geometrically simple spiral antenna is complicated by effects, such as substrate interactions, mutual capacitance between antenna spirals, and conductor losses as the metal lines approach the dimensions of the RF skin depth.

Coupled with 3D EM simulation tools, Hyperion provides a rapid and relatively low-cost method for prototype studies of spiral inductors, along with other embedded circuit components and MEMS structures.

Secondary Ion Mass Spectrometry (SIMS)

The 50-year reign of the duoplasmatron, as the highest performance oxygen plasma ion source used for SIMS, is thoroughly over. Hyperion not only provides over 10 times higher brightness but also <50% of the axial energy spread when compared to a duoplasmatron. This step-function in ion-source performance can translate to a 20-50 times increase in beam current density and sample throughput.

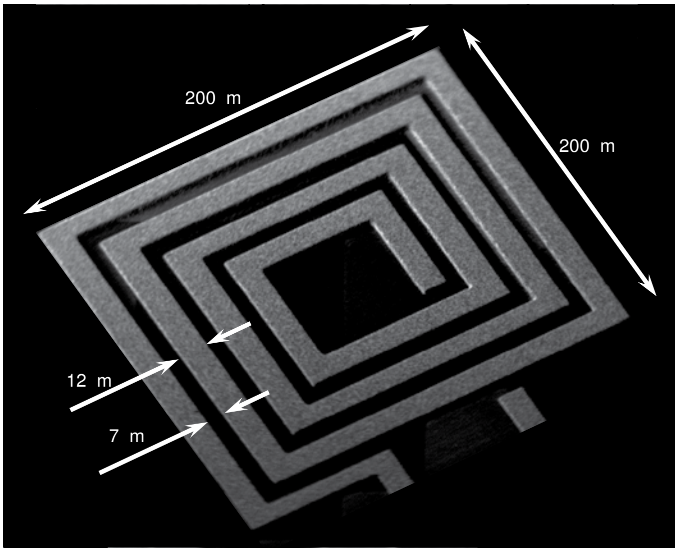

Figure 5: Prototyped copper-on-silicon oxide spiral antenna. 2.5 nH inductance for wireless RF IC.

In the semiconductor industry, it is necessary to quantitatively measure the "in-depth" distribution of dopants used for ultra-shallow junctions and ultra-thin gate dielectrics. For SIMS to be able to accurately measure the distribution of these structures, it has become necessary to bombard the surface under analysis with ultra-low energy oxygen ions in order to minimize the depth of the amorphized surface. Oxygen-focused ion beams with kinetic energies of <250 eV are often used today for this type of analysis, whereas next generation devices will require ion energies as low as 100 eV [7]. Unfortunately, the low sputter yield at these ion energies, along with the challenges of forming high-current density-focused ion beams at such low energies, has made this type of analysis very time consuming. For example, at the 32 nm node there are implanted junctions at depths of only 10 nm with post-anneal concentration gradients of the 1-2 nm/decade. A 150 eV profile of these structures today can take 8 hours with duoplasmatron-based SIMS tools. However, Hyperion can bring this analysis time down to ~30 minutes to make this type of analysis routine.

Figure 6 shows the potential gain in current density with the addition the Hyperion source to a so-called Floating Low Energy Ion Gun (FLIG™—trademark of Ionoptika Ltd) employed by many quadrupole SIMS instruments.

Here, we compare spot size (16-84 percent edge resolution) versus beam current for the prototype FLIG of Dowsett et al. [8] for a sample impact energy of 500 eV and an ion column transport energy of 5.5 keV. An optical model has been constructed for this ion beam system with the duoplasmatron curve (black line in Figure 6) closely matching experimental data collected by this author.

The Oregon Physics Hyperion ion source comfortably provides a brightness of 2500 Am^{-2}sr^{-1}V^{-1} for O_2^+ ions (4500 Am^{-2}sr^{-1}V^{-1} when O$^+$ is included) with an axial energy spread of 5 eV. Calculations show that replacing the duoplasmatron with the Hyperion source and an additional lens positioned

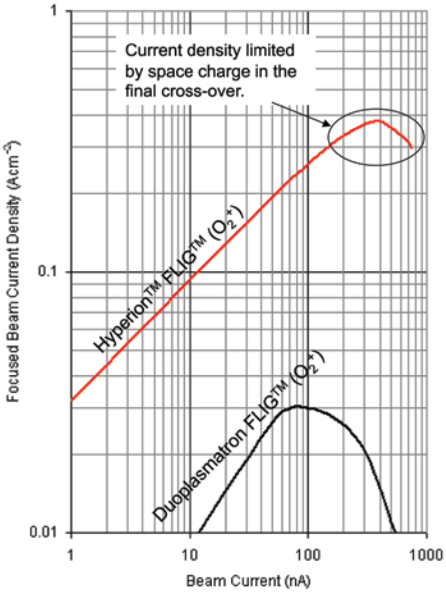

Figure 6: Comparison of the duoplasmatron ion source (black line) with Hyperion (red line) for low-energy SIMS.

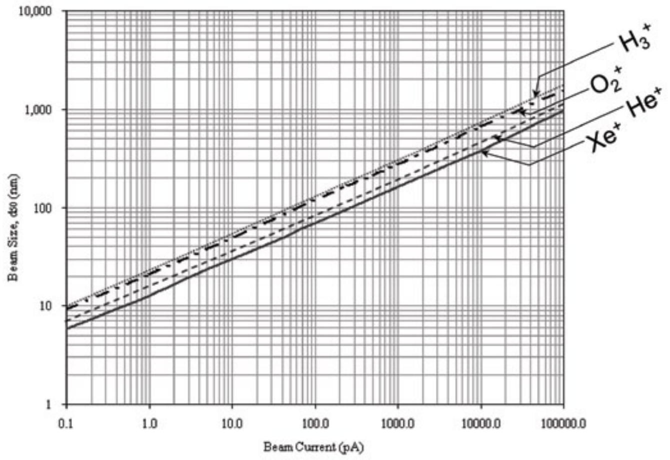

Figure 7: 150keV Nano-Implantation with Hyperion and a NanoFAB150 (MBI).

immediately after the extraction optic would result in the performance indicated by the red line of Figure 6. The additional lens operates with a shorter object side focal length than the existing condenser lens to allow for lower angular magnification, avoiding the issue of gross spherical blur at high-beam currents.

This duoplasmatron-FLIG has a peak current density in the final probe with a beam current of ~100 nA at 500 eV. Operating with a third lens, the Hyperion FLIG has a peak current density that is a factor of 10 higher at a current of 400 nA. Above 400 nA, global space charge effects in the final cross-over limits the current density.

On occasions when a large area depth profile is a requirement for the best detection limit, Hyperion would be capable of providing a gain in current density and analysis speed of a factor of 40-100 with beam currents in the range of 500-1000 nA. This added enhancement is partly due to reduced optical aberrations because the added lens operates with the shorter object side focal length. The added enhancement is also partly due to the higher brightness and lower energy spread.

For high energy (10-30 keV) SIMS imaging, the lateral image resolution is ultimately limited by the size of the collision cascade. However, to date the performance of the duoplasmatron oxygen ion source has not been sufficient to come close to this theoretical limit. With a 3-lens focusing ion column, operating with a short objective lens focal length of ~20 mm, it is possible to focus a 10 pA oxygen beam to ~150 nm at 30 keV with the duoplasmatron. Because we are again operating at the chromatic limit, Hyperion provides a factor of 50 higher optical performance and an imaging resolution at or very close to the theoretical limit.

Nano-Ion Implantation

Nano-focused ion beams can write arbitrary patterns on a target sample without the need for a mask. The LMIS has been employed by various high-energy FIB systems to provide nano-scale maskless ion implantation, but again this ion source provides a limited selection of ion species that are suitable for the semiconductor field [9]. The attraction of FIB implantation is that it is a very flexible, maskless and resistless process, where the dose can be varied from point to point on a wafer. Thus one can vary the dopant dose across a device as well as from die to die. Hyperion can not only provide a high brightness solution for ion projection lithography systems, but also has the potential to create sub-10 nm resolution beams with a range of useful ion species for focused ion beam lithography.

The MicroBeam NanoFab 150 system has been in existence for over 30 years and is based on technologies developed at Hughes Electronics Inc. However, it remains one of the most advanced ion optical systems, providing ion energies of up to 150 keV and frequently employed for modifying the electrical and optical properties of semiconductor materials. The system utilizes a two-lens optical column and an $\mathbf{E} \times \mathbf{B}$ filter with a mass resolution of ~50.

Extrapolating from our demonstrated ion source performance, calculations show that the Hyperion source operating on this system—again with an extra lens added to match the source to the column—would result in a system for up to 150 keV nano-implantation with sub-10 nm resolution with beam currents between 0.1 and 1pA. Figure 7 shows the anticipated performance of the source, coupled with the NanoFab 150 Direct Write Implanter for a select few ion species. Even with a beam current of only 0.1 pA, patterned ion implantation over a 10mmx10mm field of view could take less than 5 minutes for a moderate areal dose of $1x10^{14}$ cm^{-2}.

Conclusions

Hyperion is a plasma ion source that operates with a maximum energy normalized brightness of $1x10^4$ $Am^{-2}sr^{-1}V^{-1}$ and an associated axial energy spread of 5-6 eV. This revolutionary development, recently commercialized at Oregon Physics, is now consistently being used for numerous FIB milling applications with an operating lifetime that exceeds both the duoplasmatron and the LMIS. This technology is destined to significantly expand the capabilities of ion beam techniques used in surface science and engineering in the coming months and years. MT

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[10] The figure-of-merit at the chromatic limit is the energy normalized source brightness β_r, divided by the square of the axial energy spread, ΔE for the source (ie $\beta_r/\Delta E^2$). Focused beams typically operate in this regime with high-energy/low-current beams and low-energy beams.

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