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The ALIS He ion source and its application to high resolution microscopy

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Abstract

A new high brightness He ion source is described in terms of its basic operation, its optical properties, and its use in a high resolution microscope. A key advantage of being able to use ions to form a focused beam is the much reduced diffraction effect, as compared to an electron beam. In fact, based on the source optical properties, a column has been designed that will focus the beam to a minimum size of 0.25 nm. In turn this column is combined into a scanning ion microscope, which will allow for generating images with sub-nm resolution. The much reduced interaction volume of the He ions in the sample allows for images with remarkable surface detail and topography. Further imaging modes based on backscattered He ions from the sample provide excellent material contrast.

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Keywords:Helium ion source; Scanning ion microscope; Sub-nm image resolution

1. Introduction

Over the past decades there have been continuous efforts to develop high brightness ion sources [1]. Much of this work has concentrated on ion species suitable for direct micromachining of materials, in other words high mass ions. Indeed there has been considerable success using various types of liquid metal ion sources (LMIS), most notably with those based on gallium [2]. However there remains an application for a high resolution ion beam, used purely for imaging. A tool based on such a source would resemble the more familiar SEM, and can be simply called a scanning ion microscope (SIM).

There are 2 key advantages of using an ion beam for imaging, as compared to an electron beam. First, the effective wavelength of an ion is significantly shorter than for an electron. Given that diffraction imposes a fundamental limit on the probe size of a modern SEM, the shorter wavelength of the ion will substantially reduce

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this limitation. Second, the interaction volume of the ion beam with the sample is much smaller for ions, especially in the critical first nm of depth. In turn this means the secondary electrons generated by the ion beam will be localized to the area around the beam impact point on the specimen, allowing for more surface detail to be resolved.

In order for an ion source to be useful in an imaging application it should be based on a light mass ion. This will reduce the sputtering damage caused by the ions [3] to a level that is commensurate with imaging small details. Ideal candidates are thus hydrogen and helium (He). Of these He is the better choice due to it being a noble gas, which will minimize any chemical, electrical, or optical alteration to the sample.

In this paper a new He ion source will be described, that has suitable properties for use in a high resolution SIM. The column design for such a source is outlined, along with expected probe size values. Finally a discussion of the image contrast mechanisms available on the new SIM is presented, with example images.

2. The ALIS He ion source

The ALIS He ion source can be likened to the field ion microscope (FIM) developed over 50 years ago by Müller & Tsong [4]. Details of how the source operates have been published elsewhere [5], but will be described briefly here. A sharp needle, with an end radius of around 100 nm, is biased at a positive voltage with respect to an extraction electrode. This needle is then cryogenically cooled, and an imaging gas (in this case He) is admitted to the vicinity of the needle. In certain areas at the very tip of the needle the electric field strength is sufficiently high to cause field ionization of the He atoms, which will then be accelerated away from the needle.

From the FIM it is known that the areas of highest field (called ionization disks) occur over those atoms that protrude the most at the tip surface. In the ALIS He ion source careful control of the voltage and tip end form limit these disks to just a few atoms, as shown in Fig. 1. Here each bright disk represents ionization of He at a single atomic location. Measurements indicate that a single atom can produce currents in excess of 10's of pA. Thus the emission from just one of these atoms is selected to form the ion beam for the microscope (the other ions are sent to a suitable beam dump).

Fig. 1. The FIM pattern for the ALIS He ion source.

The size of the ionization disk is clearly smaller than the atomic spacing. Further, if the ions leaving this disk are back traced to the virtual source then the resulting virtual source size will be smaller still, although at this time no definitive measurements of this size have been made. Even assuming the virtual source size is of the order as the ionization disk (worst case) yields a source brightness of 4×10^9 A cm^{-2} sr^{-1} for normal operating conditions. This is higher than for a Schottky electron emitter, and considerably higher than for a Ga LMIS.

Initial measurements of the energy spread of the ions leaving the tip have been made. An upper bound of 1 eV has been established, but this was limited by the quality of the spectrometer used for the experiment. Other researchers have measured an energy spread in the range of 0.25 eV to 0.5 eV [6]. These values rival those of field emission electron sources, and are much lower than for LMIS.

3. The He ion column and microscope

Based on these source properties a suitable column can be designed. Given that the goal is to produce a SIM many elements of the design are similar to that of an SEM. As such it is worth examining the design in comparison to a typical SEM.

In a typical low voltage SEM the ultimate probe size is limited by a balance between diffraction and chromatic aberration effects. Fig. 2 shows how these factors vary with the image side beam convergence semi-angle α_i (also included is the effect of spherical aberration). As can be clearly seen diffraction decreases with increasing α_i, whereas chromatic aberration increases. An optimum operating point is roughly where these 2 lines cross, at $\alpha_i \approx$ 8 mrad.

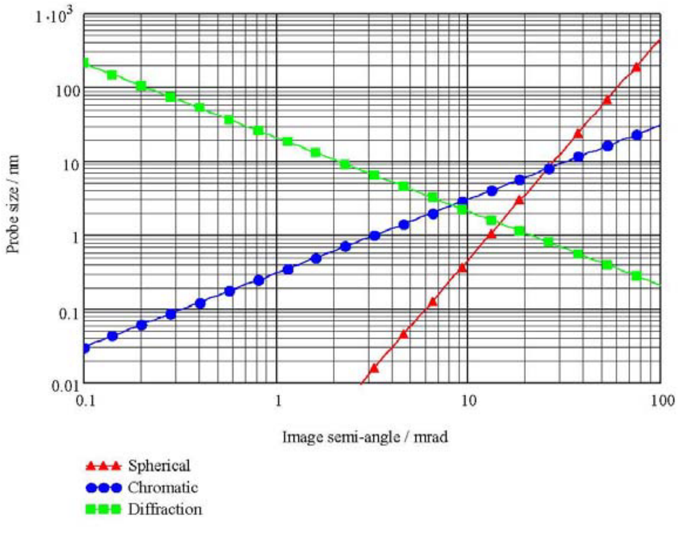

Fig. 2. Probe size versus image semi angle for a typical low voltage SEM.
The individual contributions of diffraction, chromatic aberration, and spherical aberration are shown.

For a He ion beam the diffraction effect will decrease, due to the higher particle mass and the fact that ion beams are typically operated at higher accelerating voltages. The chromatic aberration contribution will typically decrease only a small amount. Here, although the ion beam operates at a higher accelerating voltage (reducing chromatic effects) the chromatic aberration coefficient of the focusing column will be larger (the performance of electrostatic versus magnetic lenses). Fig. 3 shows how these factors contribute to the final probe size, again plotted against α_i.

The optimum operating point is again where the diffraction and chromatic lines cross, but it occurs at a much smaller $\alpha_i \approx 0.3$ mrad, giving a final probe size of approximately 0.2 nm.

For an SEM running at high resolution the effects of source brightness are assumed to be negligible (the so-called low current approximation). This is typically acceptable since the diffraction term will dominate (the brightness term is proportional to (1/ α_i) just like diffraction). For the ALIS He ion beam though this is no longer necessarily the case, and so this effect needs to be considered in the final probe size.

For the minimum brightness quoted earlier (4×10^9 A cm^{-2} sr^{-1}) and a beam current of 1 pA it can be shown that the brightness term is about twice the diffraction term. This increases the expected probe size to approximately 0.25 nm, at $\alpha_i \approx 0.5$ mrad. It is expected that future improvements and understanding will cause the source brightness value to increase (for example once the virtual source size is better known), allowing us to approach the performance shown in Fig. 3.

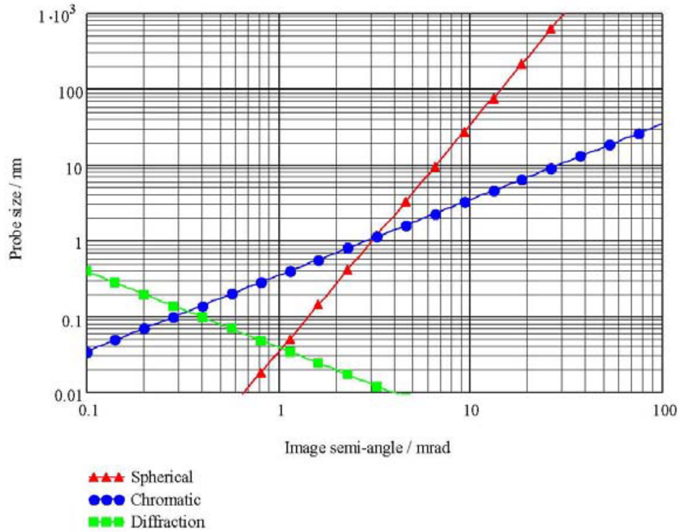

Fig. 3. Probe size versus image semi angle for a typical He ion SIM.
The individual contributions of diffraction, chromatic aberration, and spherical aberration are shown.

One key consequence of operating at a smaller value of α_i relates to depth of field (sometimes called depth of focus) d_f, which is given by the following equation.

$$d_f = \frac{\delta}{\alpha_i} \tag{1}$$

Here, δ is the minimum feature that can be resolved in the image. For any given value of δ then d_f will be up to 20 times greater for the ALIS He column, when operated under optimum conditions. It should be noted however that some of this advantage may be lost, since the He column is capable of smaller values of δ (better image resolution).

The ALIS He column design consists of two electrostatic lenses, a deflection system and a system to maintain beam alignment. It is designed to run at accelerating voltages up to 30 kV. Such a column has been constructed, and is currently being tested as part of a commercial product.

4. Sample interactions and contrast mechanisms

When the primary He ion beam hits a sample it will generate a number of different particles that can be used to generate an image. The two most notable are secondary electrons (SEs) and scattered He ions, each of which will be described in more detail below.

By definition SEs have low energy (<50 eV by convention), and are thus considered to be a 'surface signal' (the escape depth for an SE is sample material dependent, but is typically of the order of a few nm). In the case of the SEM and a bulk sample the SE signal is actually comprised of 2 components, namely SE1 and SE2. The SE1 signal is generated by the incident electron as it first passes through the sample, whilst the SE2 signal is generated by the incident electron after it has been scattered within the sample such that it again approaches the sample surface. It is known that the SE2 signal can be generated at a (relatively) large distance from the primary electron impact point, making it inherently a low-resolution signal (the SE1 signal being inherently high resolution). This leads to the concept of an SE interaction volume, which is simply that volume near the surface of the sample from which an imaging SE can be generated.

An understanding of the size of the interaction volume can be gained by doing Monte Carlo plots of the primary particle as it scatters within the sample. Fig. 4 shows such plots for 3 different incident beams, namely 30 keV Ga ions, 1 keV electrons, and 30 keV He ions, into a Si sample. For both the Ga and electron case it can be seen that there are a significant number of SE generating events within the first few nm of the sample surface that occur at a significant distance from the beam impact point, leading to a large interaction volume. However for the He case the vast majority of such events occur very close to the beam impact point, leading to a much smaller interaction volume. This smaller SE interaction volume leads to SE images that have greater surface detail.

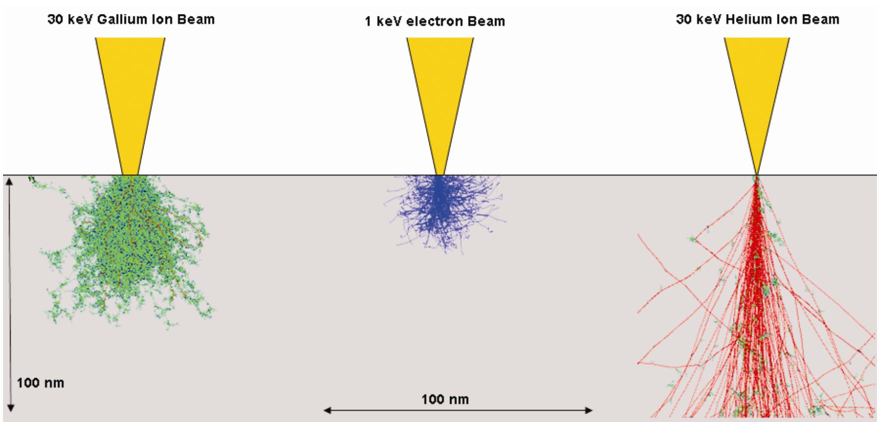

Fig. 4. Monte Carlo plots showing scattering of various incident particles in a silicon substrate.

Further, experiments to measure the SE yield for a He ion for a variety of different materials have been performed. The measured values were found to be in the range of 2 through 8 secondary electrons per incident He ion. This high average yield value leads to images with good signal to noise ratios, where as the large dynamic range in yield provides for excellent image contrast. Further experiments showed that the SE yield for He ions have a sec(α) distribution, where α is the angle of the incident beam relative to the sample normal. Thus SE images from He show the usual topographic information which makes an SIM image easy to interpret.

All of these points can be seen in the SE image shown in Fig. 5, generated using a 20 keV He beam. For comparison Fig. 6 shows an SE image of the same sample, generated using a 5 keV electron beam. The increased surface detail can easily be seen in the He ion image. Further this image shows a lot of material contrast, it is clear that the material inside the cross is different than on the outside. No such contrast is obvious in the SEM image.

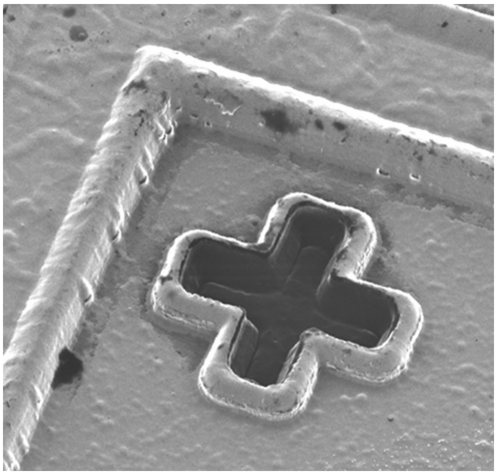

Fig. 5. SE image of an alignment cross, generated using the ALIS He ion beam.

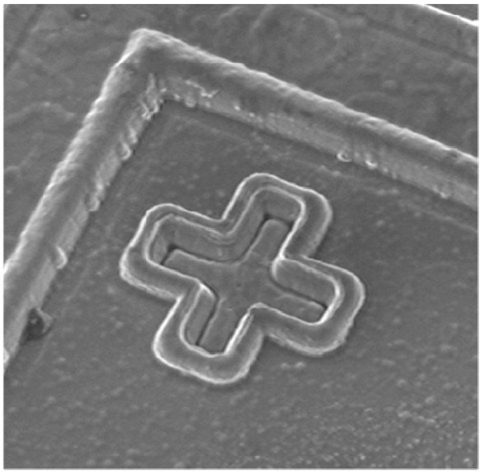

Fig. 6. SE image of the same alignment cross, generated using an electron beam.

A number of the incident He ions will simply be scattered off the nuclei of the sample, in a process akin to Rutherford backscattering (these ions are referred to as RBIs). In fact the number of such ions is proportional to the scattering cross section, which is in turn proportional to square of the atomic number of the target atoms. Thus if an image is formed using these RBIs it will contain valuable material contrast, as shown in Fig. 7. In this case the sample was formed from a number of different materials (C, Ni, Cu, and Au), and imaged using RBI. A histogram of the pixel intensity of the outlined area was then formed, and it clearly shows four peaks corresponding to each of the different materials (C being the darkest and Au being the brightest). Thus the RBI image provides for qualitative material analysis (quantitative analysis would be possible based on the energy and angle of the scattered He ion).

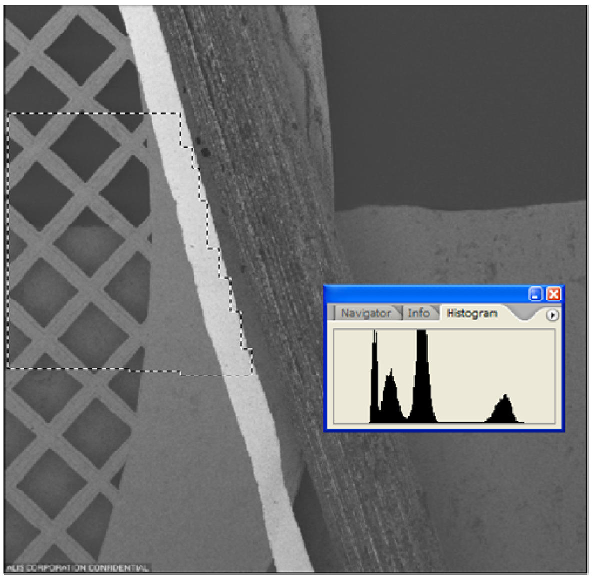

Fig. 7. RBI image of composite sample. Histogram of outlined area showing 4 distinct peaks corresponding to C, Ni, Cu, and Au.

5. Conclusions

A scanning ion microscope has been described that is based on a new He field ionization source. The source has extremely high brightness and low energy spread, leading to a focused probe size as low as 0.25 nm with a suitable column. The advantages of using incident He ions over electrons to form SE images have been shown. Further a new image contrast mechanism based on RBIs has been described, that has excellent material discrimination.

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