An Introduction to Helium Ion Microscopy and its Nanotechnology Applications

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ABSTRACT

A new imaging technology based on a scanning helium ion beam has been realized. This technology has several advantages over the traditional SEM. Due to the very high source brightness, and the shorter wavelength of the helium ions, it is possible to focus the ion beam to a smaller probe size relative to a SEM. Also, as the ion beam interacts with the sample, it does not suffer from a large excitation volume, and hence provides sharp images on a wide range of materials. Compared to a SEM, the secondary electron yield is quite high - allowing for imaging with currents as low as 1 femtoamp. The detectors provide information-rich images which offer topographic, material, crystallographic, and electrical properties of the sample. In contrast to other ion beams, there is no discernable sample damage due to the relatively light mass of the helium ion.

Keywords: SEM, FIB, Microscopy, Imaging, Helium, Contrast

1 THE ION SOURCE

In recent decades there have been many efforts to develop a high brightness source of noble gas atoms with a low energy spread. A recent summary of these efforts, and their limitations, can be found in the literature [1]. The properties of high brightness and low energy spread are desired so that the beam of ions can be focused to the smallest possible probe size on the sample. A beam consisting of noble gas ions is preferred to minimize any chemical, electrical, or optical alteration of the sample. And in the special case of helium, there is the additional benefit of no sputtering.

The ALIS Corporation has developed a high brightness, monochromatic source of noble gas ions, which is well-suited to high resolution microscopy. The ion source developed at ALIS Corporation is best understood by comparison with a related technology, the Field Ion Microscope (FIM).

1.1 A Closely Related Technology: The Field Ion Microscope

The field ion microscope was invented in 1955 by E. Müller, and K. Bahadur. The concept relies upon a cooled (T~78 K), sharp tip(R ~ 100 nm) in a UHV vacuum system, to which small amounts of helium gas has been admitted. In its simplest form, the geometry is shown in Figure 1.

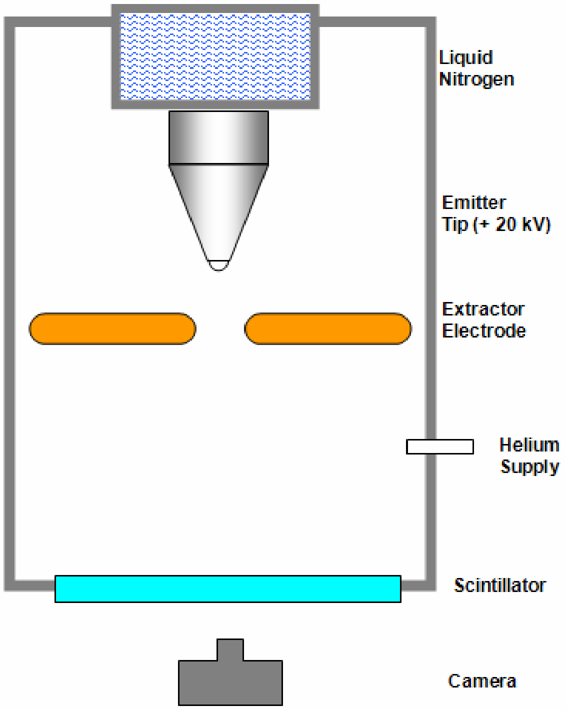

Figure 1: The geometry of a simple Field Ion Microscope (FIM).

The sharp tip is most commonly made of tungsten, and the point is commonly achieved by standard electro-chemical etching procedures. When the tip is positively biased in the presence of an adjacent electrode, a very large electric field forms at the tip. The maximum field is of course at the sharpest corners, and with only modest voltages (5kV to 30kV) a field strength of 5 V/Å can be achieved. At this field strength, the tungsten atoms from the sharpest corners will be field evaporated from the bulk. By this process, the end shape is significantly smoothed until the sharpest corners reside at steps of the crystal planes. At a reduced voltage, corresponding to a field strength of 3 V/Å, the tungsten will not be field evaporated, but any neutral gas atoms in the vicinity of the sharpest corners will be ionized by the process of electron tunneling. This ionization region is disc shaped with a diameter of just a couple of Å, and a thickness of 0.25 Å. The resulting positive ion is immediately accelerated away from the tip. Each such corner atom thus produces a beam which is usually imaged by allowing it to strike a scintillator. The ionization disk is shown in figure 2. A typical FIM image is shown in figure 3.

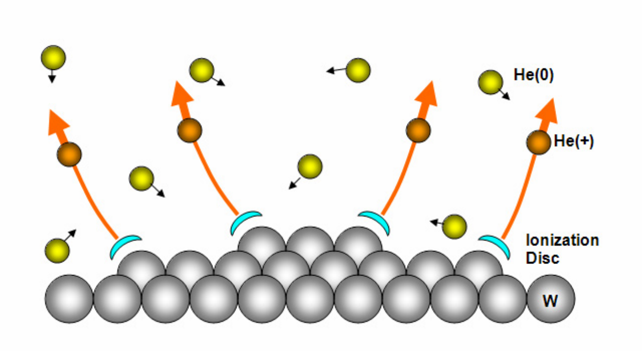

Figure 2: Neutral helium atoms (yellow) are drawn towards the tip by polarization effect. When they pass through the ionization disk (blue) they are ionized (orange) and are accelerated away from the tip.

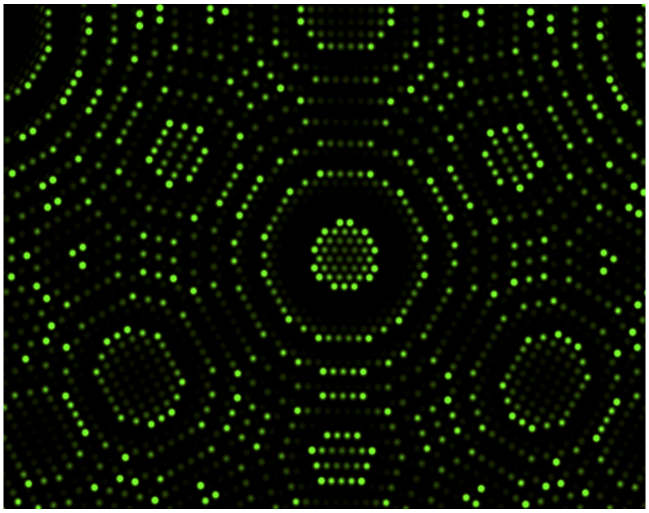

Figure 3: A typical FIM image shows many helium beams. Each beam emanates from an ionization disc above the corner atoms.

1.2 The ALIS Gas Field Ionization Source Explained

The ALIS Gas Field Ionization Source differs from the FIM principally in the shape of the tip. The tip shape has been manipulated so that there is a pyramid shaped bump on the end (figure 4). The pyramid edges and apex are atomically sharp. The advantage of this geometry is that the first few ionization discs (at the tip of the pyramid) begin emitting at a relatively low voltage while all the other atoms are not yet capable of emitting. As such, all of the arriving helium gas is shared by just a few atoms instead of a few hundred atoms (Figure 5). Under normal operating conditions the emission from a single atom is selected with an aperture. This permits the beam to have ~ 100X the beam current relative to the low current "beamlets" from the FIM.

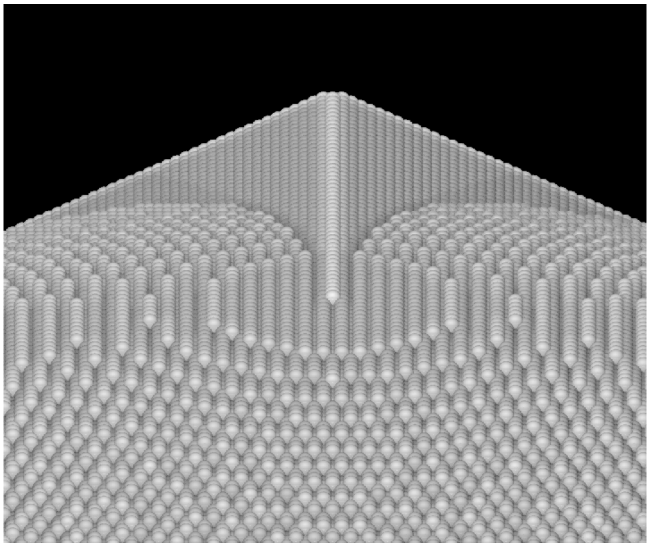

Figure 4: The ALIS source is comprised of a tungsten tip (R ~ 100 nm) with an atomically precise pyramid assembled upon it.

This pyramid can be readily removed by increasing the field to 5 V/Å until all pyramid atoms are removed. Subsequently, the pyramid can be rebuilt, and then removed an unlimited number of times by a proprietary process.

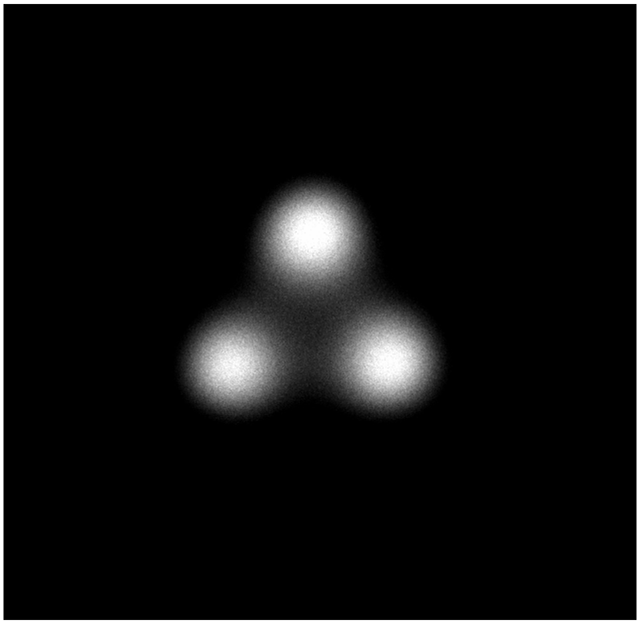

Figure 5: The emission pattern from an ALIS ion source consists of a small number of beams – each of which originates from an atom near the top of the pyramid.

1.3 Advantages of the ALIS Gas Field Ionization Source

One advantage of the ALIS source is that the beam current can be modulated by simply changing the background pressure of the imaging gas. This can be controlled over several orders of magnitude without any need to change the beam energy, extraction field, or beam steering. Under typical conditions, the beam current from a single atom is 10 pA, but operation from 1 fA to 100 pA is practical.

The energy spread of an ALIS ion source is less than 1.0 eV (FWHM). The energy spread arises from the finite thickness of the ionization disc in conjunction with the very high electric field ~3V/Å throughout the disc. Measurements by the authors have established an upper bound of 1.0 eV, which is limited by the quality of our spectrometer. This suggests that the ionization disc is approximately 0.3 Å thick or less. Other measurements [2] have indicated that the energy spread is ~0.41 eV. In comparison, this energy spread is a factor of 10X smaller than a liquid metal ion source (LMIS) [1].

The virtual source size of the ALIS ion beam is remarkably small. Each ionization region is smaller than the atom spacing, as evidenced by the non-overlapping ionization discs (Figure 5). The virtual source size, constructed by back-projecting the ion trajectories once they have left the extraction area, is expected to be considerably smaller than this. With a conservative estimate of the virtual source size of ~3Å the brightness can be calculated to be ~1.4 x 10^9 A/cm^{2}sr. This is a factor of ~30X better than a Schottky electron source, and a factor of ~500X better than LMIS [3].

Finally, the diffraction effects of a helium ion beam are considerably favorable compared to an electron beam. A typical electron in a low voltage SEM has a momentum which is small enough that diffraction effects have to be accounted for. In comparison, the ion in a helium ion microscope has a momentum which is 300X larger. And correspondingly, the De Broglie wavelength is 300X smaller for the ion.

In summary, the ALIS ion source has an energy spread, brightness, and wavelength which are well-suited to producing a high quality beam that can be focused to a sub-nm probe size – even under practical imaging conditions.

2 BEAM-SAMPLE INTERACTION

The beam-sample interaction plays a very important role in determining image quality. The ALIS helium ion microscope provides an interaction mechanism which produces high resolution images with strong and meaningful contrast mechanisms.

2.1 The Interaction Volume of the Helium Ion Beam

When a SEM beam strikes a sample, it excites a volume which is much wider and much deeper than the nominal probe size. Even if the probe size is as small as 2.0 nm, the SEM excites a volume of the sample which can be 10 nm wide and 10 nm deep (the orange region in figure 6). Secondary electrons can be generated anywhere in the top surface of this volume (indicated in red). In most cases, the image resolution is determined by the width of this region. The size of the interaction volume depends critically upon the materials being imaged, but in most cases, it is considerably larger than the advertised probe size.

In comparison, the helium ions possess considerably more momentum than an electron and penetrate correspondingly deeper in the sample before dispersing. Secondary electrons are produced throughout the volume, but only the secondary electrons near the surface can escape and be detected.

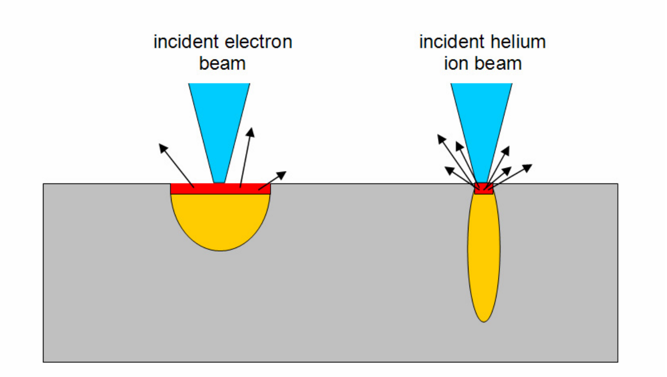

Figure 6: The incident beams (blue) produce very different excitation volumes (orange). In both cases, only secondary electrons created near the surface (red) are collected.

This narrower interaction volume of the helium ion beam serves to reduce the undesirable edge blooming artifact. For SEMs the edge blooming is quite evident and affects the ability to precisely determine the location of an edge in metrology applications.

2.2 The Contrast Mechanisms of the Helium Ion Beam

With any scanned beam system, the image is generated from a detector which is collecting a specific type of particle. Ideally, these detected particles provide the contrast mechanisms which reveal the material, topographic, and electrical properties which are of interest to the operator. At present the helium ion microscope is equipped with two detectors which provide alternative contrast mechanisms.

The first detector is a standard secondary electron (SE) detector similar to the type used in SEM's. One major difference in the SE signal, however, is in the yield. For each incident helium ion, there are a great many more secondary electrons produced. The authors have measured the SE yield for common semiconductor samples to be 5 to 20, and hence the signal to noise ratio is correspondingly better for a given beam current and acquisition time. The SE detector produces images with rich topographic information, as well as material differentiation, and voltage contrast effects. Figure 7 shows a good example of an aluminum feature on silicon.

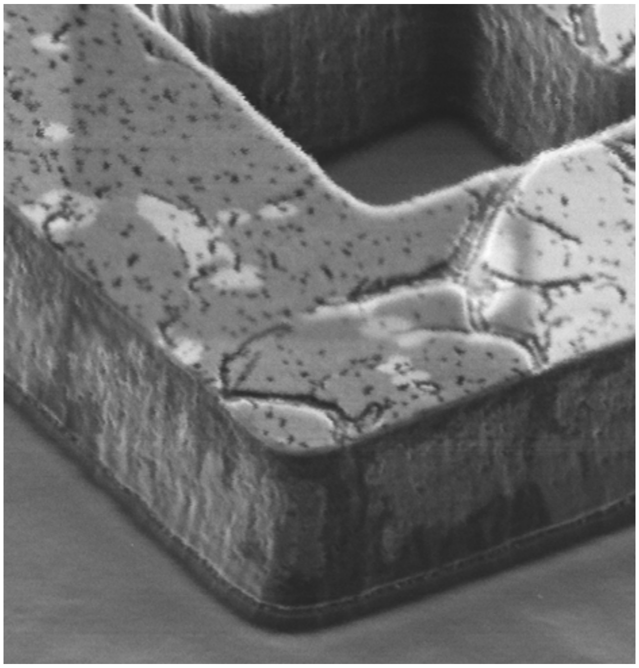

Figure 7: An SE image from the prototype helium ion microscope. The horizontal FOV is 5 um. Note the fine topographic features which are evident.

The second detector on the ALIS helium ion microscope is designed to collect helium ions that are scattered from the nuclei of the sample. This scattering process (commonly known as Rutherford BackScattering) has a probability which scales as the square of the atomic number of the target nuclei. Therefore, it produces images with a grayscale which directly maps to atomic number. Tungsten is brightest, copper is mid grey, silicon is dark grey, etc. And in sharp contrast to the SE images, there is virtually no topographic information in these images. Figure 8 shows SE and RBS images of the same feature. The feature is a laser mark which has penetrated the surface to expose a high Z material. Note how the ejected material can be readily distinguished in the right image, but not on the left.

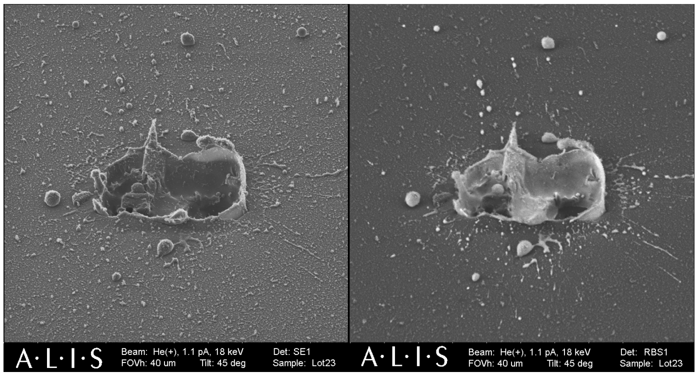

Figure 8: The SE image (left) and RBS image (right) from the helium ion microscope. The image on the right shows materials differences which cannot otherwise be discerned.

3 FURTHER APPLICATIONS

The angle and energy of the scattered helium ions can also be used to exactly identify the atomic number of the target materials along with their depth distribution. This is equivalent to the RBS analytic method but with a lateral resolution measured in nanometers, not millimeters.

The ALIS ion source is not limited to helium as an imaging gas. Helium is merely a convenient gas due to its low mass and other desirable physical and chemical properties. The imaging gas can be quickly changed to Neon or other gases if milling, sputtering, or surface cleaning is desired. Other gases can also be used to perform high resolution implantation, or localized chemical processes.

In addition to the standard SEM usage, the same source technology can be used in a transmission mode - analogous to TEM and STEM. The helium beam readily penetrates standard carbon films and can be used on properly thinned samples.

At present, the ALIS helium ion microscope is being evaluated in several industries which require nanometer resolution with strong contrast mechanisms.

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