Applications Developments with the Helium Ion Microscope

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ABSTRACT

The helium ion microscope is offering new windows into nano-scale imaging. This is due to a combination of high source brightness and unique sample interaction dynamics. These dynamics allow new types of sample information to be gathered. Some fundamental advantages conferred by probing a surface with a helium ion beam are the high contrast due to the sensitive material dependence of the secondary electron (SE) yield, the surface sensitivity arising from the low energy of the SE's, and the ability to image low atomic weight materials, such as carbon, due to the greater interaction cross-section of ions with these materials. The low mass of helium confers also a new image acquisition mode available via the collection of backscattered ions. There are also secondary benefits to helium ion microscopy. The Orion™ tool allows imaging of non-conducting samples through the use of charge neutralization via a low energy flood gun. The low mass of the helium ion minimizes beam induced damage. The much longer depth of focus of the microscope allows imaging of three dimensional objects or tilted cross-sections while maintaining focus over the entire field of view. These capabilities become even more important as the size of the features to be imaged becomes smaller than the beam-sample interaction volume found with SEM imaging.

Keywords: helium, ion microscopy, high resolution, ALIS, FIM

1 THE HELIUM ION MICROSCOPE

The helium ion microscope from Carl Zeiss SMT represents a completely new entry into the field of charged particle optics. Several workers have created and characterized gas field ion emitters in various embodiments [1]. The benefits of such an emitter are the atomic sized source ("Atomic Level Ion Source", ALIS) afforded by the principles of field ion emission and the ability to run noble gases, avoiding the use of contaminating metal ions as in the liquid metal ion source. In addition, the ability to use low mass helium ions in particular dramatically reduces the sample damage created by sputtering. Diffraction effects, which limit the ultimate spot size of an electron beam, become irrelevant since the helium ion is 7332× heavier.

The ALIS source is based upon the principles of the field ion microscope, wherein a sharpened metallic wire is cooled to cryogenic temperature and put at a high positive potential. Gas introduced into the region of the tip, after being adsorbed onto its surface by the combined action of low temperature and high field, is ionized at the electric field maximum which is found over each atomic center. The resulting ion beam from each atomic sized emitter is separated in space from all others, giving rise to a multiplicity of possible ion sources.

The key to the ALIS technology is a formation process which produces a special structure on the end of the tip, reducing the emission sites from the hundreds normally visible in the field of view in Figure 1 to a very small number. The microscope's ion gun allows for one emitter from this group to be selected for transmission through the electrostatic ion optics, yielding a single, stable ion beam with high brightness ($> 3.4\times10^9$ A-cm^2-sr). Calculations show that an 0.25nm probe size is possible with the current optics; so far measurements have achieved < 0.6nm. The interested reader may see reference [2] for further information.

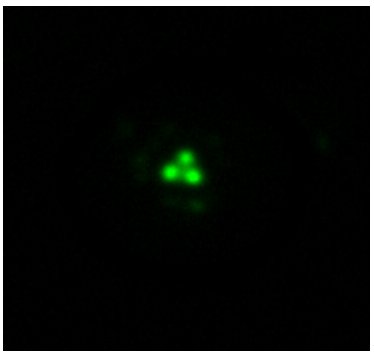


Figure 1: field emission pattern from the ALIS ion source.

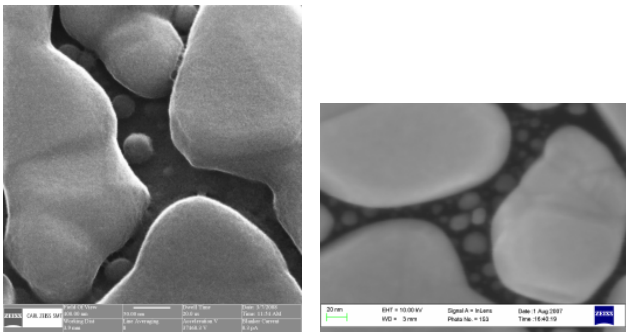
2 INTERACTIONS AND IMAGES

The sample information available from any scanning probe microscope depends only partially on the probe size.

There are several factors to consider, and the full range of beam-sample interactions determine which applications are best suited to a given technology. We present here a discussion of several of these, illustrated by applications that benefit from them.

2.1 Beam-Sample Interaction Volume

Instrument considerations notwithstanding, the image resolution from a scanning microscope depends not on the probe size alone but also on the volume in the sample from which the detected signal originates. For an electron beam, a significant portion of the SE signal can consist of type-II electrons – those which arise from backscattered electrons as they exit the sample [3]. The results in a delocalized contribution to the detected signal, which reduces lateral resolution and convolutes surface topology with sub-surface signal. For an incident helium ion beam, the secondary electron energy spectrum peaks below about 5eV and then drops off quickly. Since the escape depth of electrons of this energy is on the order of a couple of nanometers, there is no SE contribution from deeper in the sample. This can be seen more readily in high resolution images, such as the example shown in Figure 2. The sample is evaporated gold on a carbon substrate. In the helium ion micrograph on the left, we see excellent edge definition and also great topological information, including the fine surface detail on the gold particles. This arises from the combination of the sub-nanometer probe size and the true surface-only nature of the SE signal. The SEM image in Figure 1b, while able to image the small particles, suffers from a diffuse contribution to the signal everywhere. Thus the edges of the particles become slightly blurred, the smaller particles have low contrast, and most notably the surfaces of the particles look flat. Thus the combination of small probe size and small signal origination volume provides a unique benefit for high resolution imaging tasks.

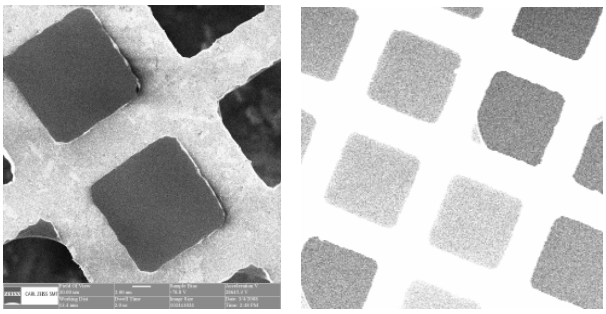


(a) (b)

Figure 2: High resolution images of gold particles; 500nm field of view. (a) Orion™ image, (b) SEM image.

2.2 Surface Sensitivity

Related to the concept of the reduced signal generation volume is an improved ability to image thin surface layers and materials. Due to the different energy loss mechanism for a helium ion beam, more signal is generated from the top monolayers of a given sample. This effect can overcome the electron transparency that challenges SEM imaging of very thin layers and objects. This is highlighted in Figure 3, which shows an nitro-biphenyl-thiol (NBPT) monolayer which has been lifted off its substrate and then laid over a gold grid. It is very difficult to see in SEM, requiring the image to be highly saturated in order to get enough contrast to detect it (Figure 3b). This reduces resolution, however, and introduces noise. The helium ion microscope is able to image this free-standing monolayer much more readily. It is obvious from Figure 3a that even such a thin layer of this low atomic weight material is easily detected, as can be judged from the opacity of the grid windows that are covered. This ability can be leveraged into many applications, such as carbon nanotubes (cf. Figure 8).



(a) (b)

Figure 3: NBPT monolayer stretched over a gold grid. (a) Orion™ image, (b) SEM image.

2.3 Material Contrast

The ability to distinguish different materials in a sample arising from changes in the secondary particle emission from one material as compared to another. For a primary electron beam the SE yield does not change as much as a function of material as for a primary ion beam [2]. This, combined with the greater physical localization of the SE signal from a helium ion probe, allows nano-structured devices to be imaged with greater ease. This can be seen especially in cross sections of layered devices from semiconductor or magnetic storage technologies, where there are stacks of thin layers of several materials. An example of this is shown in Figure 4, which shows a cross section of a tunneling magneto-resistance device. The SEM image of the middle "H2" layer appears to be a single material with a thickness of 31nm. In the Orion™, however, this is revealed to be a triple layer. There is

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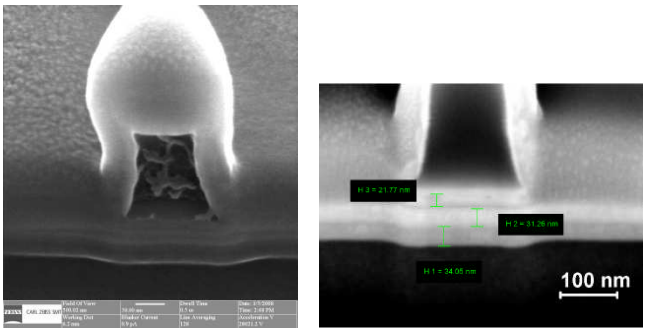
additionally a thin layer just above the substrate which is not captured at all in the SEM. This demonstrates the ability to find new information from lithographically defined structures. We have also made excellent progress in imaging 45nm technology semiconductor devices and will be publishing results in the near future.

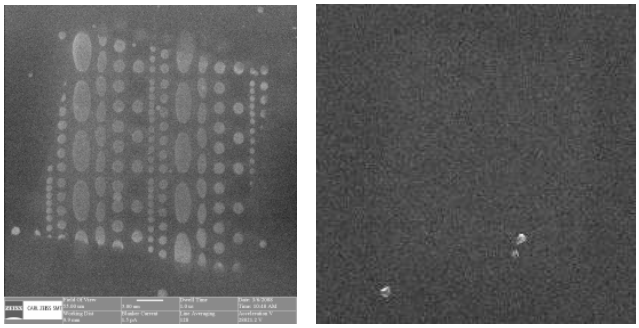
A further test of material contrast is the ability to distinguish different materials on a surface. For many applications, very thin layers may be nano-patterned via deposition, selective etching, or by beam induced chemical modification. The need exists to be able to image even single atomic monolayers that have been patterned across a surface. The helium ion microscope shows the ability to do this, as highlighted in Figure 5.



(a) (b)

Figure 4: Tunneling magneto-resistance layer stack, viewed in cross section. (a) Orion™ image, (b) SEM image

The sample imaged in Figure 5 is a NBPT doubled monolayer, the same as in Figure 4, but now over a gold film. It has been patterned by e-beam exposure via a contact mask. The exposure converted the nitrate terminal group to amine. Thus the only contrast mechanism available for imaging these patterns are the substitutions of hydrogen for oxygen on the top monolayer of the surface. The SEM image in Figure 5b shows that it is just possible to start seeing the 40 micron window where exposure had occurred. With the helium ion microscope, however, there is very clear chemical contrast that allows the full pattern to be seen easily. This makes the Orion™ to be a powerful tool for investigations of surface modifications and patterns.



(a) (b)

Figure 5: NBPT double layer over a gold film, patterned with an e-beam mask. (a) Orion™ image, (b) SEM image.

2.4 Backscattered Ion Imaging

A new imaging mode available when imaging with helium ions comes from the collection of Rutherford backscattered ions (RBI mode). Due to the low mass of helium it will backscatter from every element except hydrogen. Since the backscatter probability rises with the atomic number of the target, there is an inherent strong material contrast provided. We have collected RBI data on a set of pure elemental test samples for all the conducting elements from boron to bismuth, as presented in Figure 6. The scatter points show the experimental data, while the solid line shows TRIM simulations for the same beam energy (25keV). There is a good fit of the overall shape, allowing for a qualitative mass mapping in the images. There are peaks in the experimental data, occurring in each period of the elements, centered approximately at the noble metals Cu, Ag, and Au. The origin of these peaks is not explained and not predicted by TRIM. This effect enhances chemical contrast in RBI mode images but also makes quantitative determination of species uncertain. We are working to combine the RBI information with energy selective backscatter detection to provide true elemental identification at deep sub-micron resolution.

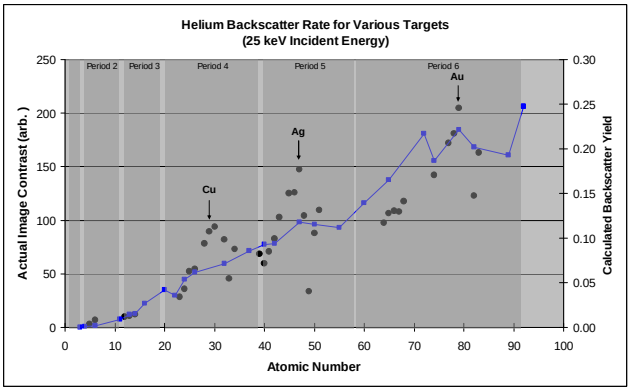


Figure 6: A comparison of experimental and simulation data on the backscattering of 25keV helium ions from a wide variety of chemical elements.

3 ADDITIONAL BENEFITS

We touch briefly here upon two of the additional features of helium ion microscopy and their benefit to specific applications.

3.1 Charge Control

Imaging for samples which charge under a beam will suffer from distortions, noise, loss of contrast, and other image artifacts. Low energy SEM, with the beam energy near the unity SE emission point is often used to deal with this – but at a loss of resolution due to decreased beam

brightness. Ion beams allow the neutralization of charge through the use of a low energy electron flood gun to dissipate the build-up of positive charge. The Orion™ microscope is equipped with a flood gun for handling insulating samples. An example of this capability is highlighted in Figure 7. The sample is a chrome on quartz photomask. The electron flood, applied in multiplex with the ion beam, allows for very stable imaging which brings out the shape of the chrome line, the details of the chrome grain structure and the interface between the metal and the quartz.

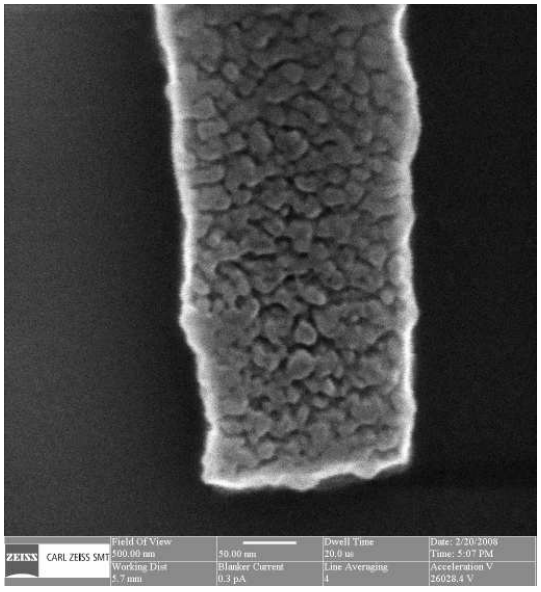


Figure 7: Chrome line on a photomask imaged using charge neutralization.

3.2 Depth of Field

When imaging three dimensional structures or tilted surfaces, it is beneficial to keep as much of the region of interest as possible in focus. This becomes difficult to achieve as the image magnification increases, for the beam convergence angle becomes higher. The low angular divergence of the beam in the ALIS source, combined with the small source size (requiring less de-magnification at the image plane), allows for a depth of field about 5 times greater than an SEM under similar conditions. This is evidenced in Figure 8, where the investigation centered on single walled carbon nanotubes grown on SiGe catalysts. It was found that the nanotubes preferred to grow in a network connected amongst the catalyst particles and suspended in free space over the silicon substrate. For this reason the image in the Figure was taken at a sample tilt of 70°, in order to see beneath the network. Even at this high viewing angle the nanotubes remain in focus, both in the foreground and the background.

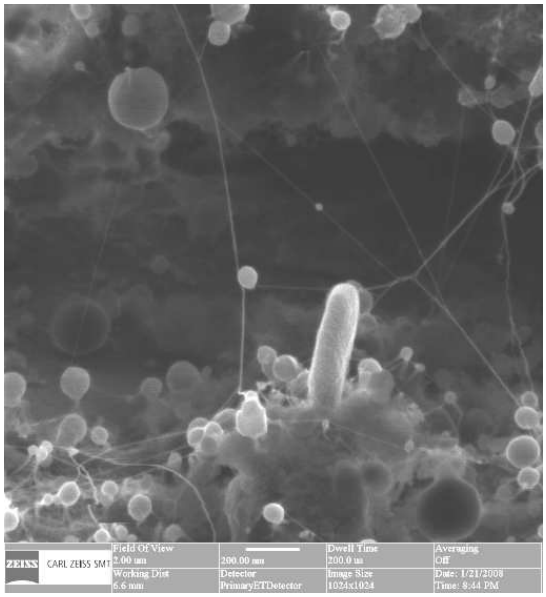


Figure 8: Single wall carbon nanotubes suspended above a silicon surface on SiGe catalyst particles. 70° tilt of sample from beam axis.

4 CONCLUSION

This has been a brief survey of a subset of the capabilities being developed for the helium ion microscope. We hope to have demonstrated that this technology can provide a wealth of information complementary to, and in some cases even beyond, SEM. We continue to research the capabilities for new applications, as we drive to further establish this technology in the microscopy community.

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REFERENCES

[1] V. N. Tondare, J. Vac. Sci. Technol. A, 23 (6), p.1498 (2005).
[2] J. Morgan et. al., Microscopy Today, 14 (4), p.24 (2006).
[3] D. C. Joy et. al., SPIE Proceedings: Metrology, Inspection, and Process Control for Microlithography XXI 6518, (2007).