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Comparative Analysis of Helium-Ion Microscopy and Scanning Electron Microscopy in Nanofabrication and High-Resolution Imaging

Yun Chen [1,*], Yufei Hu [2], Sixu Li [3], Chenxu Wang [4]

[1] Physics and Electronic Engineering, Hengyang Normal University, Hengyang, Hunan, 421009, China

[2] Manchester Metropolitan Joint Institute, Hubei University, Wuhan, Hubei, 430062, China

[3] School of Electrical Engineering, Hebei University of Technology, Tianjin, 300401, China

[4] College of Physics and Technology, Tianjin Polytechnic University, Tianjin, 300387, China

* Corresponding author: 2113720113@tiangong.edu.cn

Abstract. With the development of science and technology, scientists' demands for fineness in fields such as semiconductors, materials, and bioimaging are increasing day by day. Traditional electron microscopes have certain limitations in observing the microstructure of substances. The helium ion microscope (HIM) has a higher imaging resolution and more refined nano-processing capabilities, playing a breakthrough role in the development of science and technology. In this paper, the literature analysis method is used to retrieve, collect, and compare different literature. Firstly, it introduces the important role of the HIM in the fields of materials and nanofabrication. Then, it introduces the development background of the HIM and specifically analyzes its imaging principle. Next, it compares it with the scanning electron microscope, analyzes the similarities and differences between the two, and points out the problem of its high cost. Moreover, it discusses the application prospects of the HIM in high-resolution imaging and high-precision nanofabrication. Finally, it is concluded that the HIM has high accuracy and precision in the field of fine-processing materials.

Keywords: Helium Ion Microscope; High-Resolution Imaging; Gas Field Ion Microscope; Nanofabrication.

1. Introduction

The microscope, as an important tool for scientific research and medical diagnosis, has greatly expanded human beings' cognition of the microscopic world. A microscope is an optical instrument composed of one or several lenses and is a symbol of human entry into the atomic age. It can be used to observe the microstructure of certain microorganisms (viruses, cells). According to the different light sources used, microscopes can be divided into optical microscopes and electron microscopes.

The helium ion microscope (HIM) is a new type of microscope. It uses a helium ion beam as the light source and has a higher resolution and better surface sensitivity than traditional microscopes. Firstly, by using HIM technology, researchers can deeply explore various materials in the field of materials science, including the microstructure and properties of materials such as composites, metals, superconducting materials, semiconductors, and insulators. By observing the surface morphology, crystal structure and other characteristics of the materials, it provides key information for the design, preparation and performance optimization of the materials. Secondly, the HIM has wide applications in nanotechnology research and can analyze key factors such as the morphological characteristics and distribution of nanomaterials. This technology helps researchers understand the physical and chemical properties of nanomaterials more deeply and guides the preparation and application of nanodevices. Among them, HIM has the nano-processing function of a focused ion beam (FIB) and the ion implantation function of an ion implanter. It can achieve efficient and high-precision processing of sub-10nm-level structures and is the only imaging and processing platform that integrates three types of ion beams of Ga, Ne, and He, covering imaging and processing applications from the micron to the nanometer scale [1, 2]. In the fields of biology, bioimaging, and bioengineering, the HIM can not only provide good imaging without the need for a conductive coating but also avoid damage caused by electron beam radiation. When Tsuji et al. studied the differences between diseased and normal glomeruli in mice, they used the HIM to obtain high-resolution imaging of the three-dimensional podocyte and endothelial interface and observed for the first time the details of distorted podocyte morphology and abnormal glomerular endothelium in the Col4a3 mutant glomeruli [3, 4]. In terms of applications in the semiconductor industry, the HIM can monitor and optimize each step in the semiconductor process, such as lithography and deposition, and can also perform nanoscale analysis of semiconductor device failures, which helps to find the causes of device failures, such as surface contamination. Among them, by comparing the charge contrast in the HIM image of the in-situ prepared graphene nanoelectrode structure, the conductance of nanoelectronic devices can be intuitively understood [5].

In this paper, through the literature analysis method, the imaging principle of the HIM is analyzed, and the differences between the HIM and other microscopes are compared. The HIM has played an irreplaceable important role in the field of advanced science and technology and provided more accurate data for the path of scientific research. This paper aims to provide a theoretical basis and reference for research and application in related fields.

2. Principle

The predecessor of the HIM is the Field Ion Microscope (FIM). In 1951, the gaseous field ion source technology had already emerged, and the first gaseous FIM was fabricated based on this technology four years later, and the atomic projection of the tungsten wire tip as the anode tip could be observed. The principle of FIM is that in a helium gas environment, due to the extremely high charge density of the protruding atoms of the anode filament in the high-voltage electric field, tip discharge will eventually occur and the electron tunneling effect will occur. Thus, the helium atoms in contact with the protruding atoms of the irregular filament tip will be ionized into helium ions. Then the helium ions continuously generated by these different tip atoms will form different continuous helium ion currents. Subsequently, these helium ion currents will accelerate along the same trajectory and hit the fluorescent screen, eventually forming a simple two-dimensional projection of the atomic structure of the filament tip. In the early days of this technology, people only used it to detect the surface structure of different crystals, that is, to make tips from different crystals, then place them in helium gas, ionize helium atoms, and then accelerate through the electric field. Helium ions hit the fluorescent screen to form bright spots. Thus, the crystal structure at the tip of the filament crystal is observed. Subsequently, the gaseous FIM developed again in the 1960s. The three-dimensional atomic probe is the result of the FIM technology combined with the single-atom recognition technology. By using a high-voltage pulse to individually strip the atoms at the tip of the probe and then measuring their flight speed, combined with the two-dimensional projection, atomic-level three-dimensional structure information can be obtained.

Combining the above technologies, the HIM came into being. A modified tungsten wire with only three atoms at the tip, where the three atoms at the tip are called trimers, is exposed as an anode in a low vacuum environment containing trace amounts of helium gas. After the acceleration of the positive electric field, the trimers at the tip of the filament will emit three helium ion currents. These three helium ion currents will be focused into a FIB after passing through the aperture. Finally, the resulting low-beam helium ion beam comes into contact with the sample surface to generate secondary electrons, thereby achieving imaging. The high-resolution advantage of the HIM is achieved by controlling the helium gas flow. The helium ion beam is controlled by adjusting the helium gas flow to adapt to different imaging requirements.

In addition to the high-resolution advantage, HIM also has other advantages. For example, non-coated observation or high-precision processing of materials with poor conductivity. When helium ions bombard the sample surface, its lighter relative atomic mass compared to other atoms enables it to cause a smaller damage range on the sample surface. Therefore, the related technology of the HIM can be used to manufacture more refined nanostructures for materials [4].

3. Comparison of HIM and Scanning Electron Microscope (SEM)

3.1. Comparison of Imaging Principles

HIM uses an ion source to produce a helium ion beam (with energies between thousands and hundreds of thousands of electron volts), which causes the helium ions to interact with the sample surface, producing signals such as secondary ions, reflected particles, and so on, which are captured by the detector and produce an image. SEM uses an electron gun to generate a high-energy electron beam, focuses the electron beam to a very small diameter through a lens, interacts with the surface of the sample, generates secondary electrons, reflected electrons, X-rays, and other signals, and collected by the detector and converted into images for display [6].

Through detailed comparison, it can be seen that the imaging mechanisms of the two are different. He uses a helium ion beam to interact with the sample and produce secondary ions; SEM uses an electron beam to interact with the sample, primarily producing secondary and reflected electrons.

3.2. Resolution Comparison

HIMs are often able to achieve lateral resolutions of better than 1 nanometer, and even close to 0.5 nanometers in some cases. In contrast, the conventional lateral resolution of scanning electron microscopy is generally between 1 and 3 nanometers. Table 1 is used for detailed data comparison.

Table 1. Resolution comparison

	Zeiss HIM	He-ne-gallium three-beam micro nano ion microscope	Zeiss multiple ion beam microscope	Model JSM6610LV SEM	SM-7800F type field emission SEM	Model S4800 high resolution field emission SEM
Resolution ratio	0.5nm	0.5nm	0.5nm	3.0nm	0.8-1.5nm	1.0-2.0nm

Through detailed comparison, it can be seen that HIMs have a better ability to observe small structures and details.

3.3. Comparison of Imaging Depth

HIM uses helium ions for imaging, and the binding energy of helium ions is lower than that of electron beams, resulting in a strong ability of helium ions to penetrate the sample and usually a larger imaging depth [7]. This allows HIM to image relatively thick samples at high resolution and is less susceptible to surface charging effects. SEM uses an electron beam, which has a weak ability to penetrate the sample and shallow imaging depth, usually only a few nanometers to tens of nanometers [8, 9].

By comparison, it can be seen that helium ion microscopy has advantages in high-resolution imaging of three-dimensional sample structures and can show deeper levels of detail.

3.4. Comparison of Sample Preparation

As for SEM, the sample usually needs to be covered with a conductive substance (such as metal or carbon) to enhance its conductivity to obtain a clear image when scanning the electron beam irradiation. In addition, SEM has strict requirements on the vacuum environment of the sample to prevent gas molecules from interfering with the imaging quality [10]. However, HIM does not require conductive treatment of the sample surface, because helium ion beams, unlike electron beams, do not easily generate charge accumulation on non-conductive surfaces. This allows HIM to achieve high-resolution imaging directly on a variety of sample surfaces, including biological samples. Furthermore, there are relatively relaxed environmental conditions during HIM operation and HIM can work in an environment close to atmospheric pressure, which is beneficial for maintaining the natural state of the sample.

By comparison, it can be seen that HIM is suitable for the situation where the surface properties of the sample are not required or the imaging needs to be performed in the natural state.

3.5. Comparison of Imaging Speed

SEM generally has a fast-imaging speed and can obtain a large range of images in a short time. However, due to the low current of the ion beam, the imaging speed of HIM is slow, which may have certain limitations for application scenarios requiring fast imaging. Table 2 provides a detailed data comparison.

Table 2. Imaging speed comparison

	Hitachi HI-9500	Zeiss Gemini SEM series HIM	Zeiss Sigma series SEM	FEI Quanta SEM
Imaging speed	Frames per second	A few frames per second to 10 frames per second	More than 10 frames per second	20 frames per second

Through detailed comparison, it can be seen that SEM has faster imaging speed and is suitable for fast imaging application scenarios.

3.6. Comparison of Cost

From a cost perspective, the equipment price of HIMs is usually more expensive than SEMs, which also limits its wide application in some general laboratories and industrial fields. Table 3 provides a detailed data comparison.

Table 3. Cost comparison

	Zeiss Orion NanoFab	FEI Helios NanoLab 660	TESCAN LYRA3	Carl Zeiss Orion NanoFab	Zeiss EVO MA15	JEOL JSM-IT500	Hitachi SU3500	JEOL JSM-7800F
Price	1,000,000-2,500,000	1,200,000-2,000,000	900,000-1,800,000	1,000,000-2,500,000	150,000-350,000	250,00-450,00	200,00-350,00	300,00-500,00

Through detailed comparison, it can be seen that HIM has a more expensive construction cost.

4. Application Fields

4.1. High-Resolution Imaging

In terms of high-resolution imaging, because the diameter of helium ions is much larger than that of electrons, most helium ions will reflect on the surface of the sample when they shine on it. Therefore, in a microscope, the secondary electronic signal received by the probe mainly comes from the surface of the sample, which makes the image presented under HIM the surface of the sample, while the internal signal is smaller [11]. Overall, the HIM has a greater depth of field and higher resolution [12]. Its applications in materials science include semiconductors, nanomembranes, two-dimensional materials, catalysts, and solar cells. In the field of life science, HIM can be used to observe tissues and organs at the cellular level, as well as texture images of nanocolumns on butterfly wings [13].

4.2. High Precision Nanofabrication

In the aspect of high-precision nanofabrication, HIM can sputter the target region by adjusting the dose of sample bombardment, and carry out high-precision nanofabrication. By switching the helium and neon ion sources in the same tube, the high-precision and rapid processing of several hundred nanometers to several nanometers can be achieved. This is because the helium ion has a relatively low mass and has a small damage range to the sample. Therefore, although the sputtering yield of the helium ion beam is lower, the manufacturing process is more controllable, with a larger depth-to-width ratio and higher accuracy [4]. Based on the above characteristics, HIM has applications in the fabrication of nanopore devices and the etching of high-precision nanostructures.

4.3. Application Prospect

The high spatial resolution of helium ion microscopy and its ability to image non-conductive samples without conductive coatings make its imaging capability far superior to that of SEM. In addition, HIM has excellent nanomachine manufacturing capabilities. Furthermore, HIM continues to conduct research in imaging and nanofabrication, including the realization of low-temperature imaging of samples and the combination of low-temperature imaging of biological samples with high resolution and nanofabrication. These developments will complement imaging studies and analyses under cryo-TEM and cryo-SEM [14].

5. Conclusion

HIM is a new ion microscope, compared with traditional SEM, it has higher imaging resolution and can nano-process samples, which makes it play an important role in a variety of research fields. This paper introduces the background and application prospects of HIM from the following four aspects.

This paper first introduces the important role of helium ion microscopy in the fields of materials, nanodevices, biomedicine and semiconductors. It is explained that HIM not only has higher resolution in observing samples, but also produces less loss to biological samples. In addition, HIM can optimize the relevant links of semiconductor processes and provide nanoscale analysis.

Then the development background and related principles of helium ion microscopy are analyzed. Gaseous FIM, the predecessor of HIM, is introduced and its principle is analyzed in detail. Finally, the imaging principle of HIM is introduced: the tungsten wire is cooled at low temperature, and exposed to the environment containing helium gas as an anode. After the acceleration of the positive electric field, three helium ion streams are emitted from the filament tip and are focused into ion beams after passing through the aperture.

Then, the HIM was compared with SEM, and it was analyzed from the aspects of imaging principle, resolution, imaging depth, sample preparation, imaging speed and cost, respectively. It was found that HIM had significant advantages in the first four aspects, while SEM was superior to HIM in imaging speed and cost control.

Finally, the application of HIM in high-resolution imaging and high-precision nanofabrication is introduced. The reason why HIM can achieve higher resolution imaging and the principle of high precision nanofabrication are analyzed. In the future, with the continuous research and development of HIM in low-temperature imaging, biological sample imaging, and nanofabrication, its application in supplementary cryo-TEM and cryo-SEM imaging research will be more extensive and in-depth. These advances will further advance HIM's important role in scientific research and industrial applications.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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