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(54) Title: SCANNING TRANSMISSION ION MICROSCOPE

(57) Abstract: In certain aspects, the scanning transmission ion microscope includes a bright helium ion source to generate an ion beam and a focusing electrostatic optical column to focus the ion beam. A translation stage supports a sample to receive the focused ion beam and a detector responds to ions transmitted through the sample to generate a signal from which properties of the sample may be displayed.

SCANNING TRANSMISSION ION MICROSCOPE

Background of the Invention

This invention relates to ion microscopy and more particularly to a scanning transmission ion microscope.

The structure of thin samples can currently be analyzed by scanning transmission electron microscopes (STEM) or by transmission electron microscopes (TEM). Both of these instruments detect changes in the primary electron beam when it interacts with the electronic structure of a sample. The focused probe used in STEM can, upon exit from the sample, provide information about the atomic spacing in the material and the atomic species through interactions that are sensitive to the atomic number Z at the beam position. TEM typically illuminates the sample all at once with a uniform electron beam so that the structure of the sample being examined imparts spatial information onto the beam. By looking at either the bright field (electrons which are transmitted) or dark field (electrons that are scattered), different types of sample information can be extracted. A TEM is a large, complex, expensive tool utilizing very high energy electrons. The use of very high energy electrons is an operational burden. STEM is somewhat simpler but cannot yield the same resolution as TEM. Its main advantage is greater contrast dependence on Z, allowing species characterization.

Atomic level surface structure from thick samples is obtainable by scanning tunneling microscopy (STM) and, to a lesser extent, by atomic force microscopy (AFM). These are slow methods that require mechanically scanning a very fine needle-shaped tip over the sample. These methods typically cannot provide information on what is below the top atomic layer of the sample, however.

A detailed understanding of the operation of the above-mentioned, presently available microscopes is held by many persons skilled in the art of high resolution microscopes. Detailed information on the theory of operation and the applications of these microscopes is readily available in the public domain. Commonly available publications include, but are not limited to, classroom text books, scientific publications, microscope vendor publications as well as various documents commonly available in libraries such as the United States Library of Congress. There are also many patents that cover these commonly available microscopes. An example of a commonly available publication provided by a microscope vendor is JEOL News, Volume 37E, Number 1, 2002. Textbooks that teach the above described microscopes include the following:

1. *Scanning Electron Microscopy and X-Ray Microanalysis by Joseph Goldstein (Editor)* .

2. *Scanning and Transmission Electron Microscopy: An Introduction by Stanley L. Flegler, et al.*

3. *High Resolution Focused Ion Beams: FIB and Its Applications by Jon Orloff Materials Analysis Using a Nuclear Microprobe by Mark B. H. Breese*

4. *Scanning Probe Microscopy and Spectroscopy: Theory, Techniques, and Applications by Dawn Bonnell (Editor)*

Summary of the Invention

In one aspect, the scanning transmission ion microscope of the invention includes a gas field ion source to generate an ion beam and a focusing electrostatic optical column to focus the ion beam. A translation stage supports a sample to receive the focused ion beam. A detector responds to ions transmitted through the sample to generate a signal from which properties of the sample may be displayed. In one embodiment, the ion beam comprises helium ions. The ion beam may have sub-nanometer beam diameter. In one embodiment, a cold finger is provided to vary temperature of the sample. The microscope may include structure to maintain the microscope in a vacuum environment. A computer may control the precise placement of the ion beam on the sample. An electron beam may be provided to neutralize charge on an insulating sample. Suitable ion beam energy is in the range of 1,000 V to 1,000 keV. In one embodiment, the translation stage is configured for at least one of tilting and translation of the sample.

Brief Description of Drawing

The following figures depict certain illustrative embodiments of the invention in which like reference numerals refer to like elements. These depicted embodiments may not be drawn to scale and are to be understood as illustrative of the invention and not as limiting in any way.

Fig. 1 is a schematic illustration of one embodiment of the microscope of the invention.

Fig. 2 is a schematic illustration showing the sample end detector regions more clearly.

Detailed Description of the Preferred Embodiments

The systems and methods described herein will now be described with reference to certain illustrative embodiments. However, the invention is not to be limited to these illustrated embodiments which are provided merely for the purpose of describing the systems and methods of the invention and are not to be understood as limiting in anyway.

With reference first to Fig 1, an ultra bright helium ion source 10 sends a beam of helium ions down a focusing electrostatic column 12. The ions impinge upon a sample 14. The sample 14 is mounted on a translation stage 16. The sample holder 16 may be equipped with a cold finger 18 to allow variation of sample 14 temperature.

Ions transmitted through the sample 14 are detected by a detector 20. A vacuum enclosure 22 surrounds the sample 14 and the detector 20 as shown. A computer 24 provides fine placement of the ion beam on the sample 14 by providing deflection voltages that may or may not be amplified along with optical control voltages that are amplified by high voltage supplies (not shown) allowing control of beam focus and deflection. A low energy charge neutralizing electron beam unit 26 provides the ability to keep charge from building up on an electrically insulating sample.

With the ion beam focused to sub-nanometer size, it may be rastered over the sample that has been preprocessed to sub-micron thickness.

The high brightness source 10 produces a helium ion beam with energy in the range of 1,000 V to 1,000 keV. A suitable bright ion source is described in "Ion Sources for Nanofabrication and High Resolution Lithography", J. Melngailis, IEEE Proceedings of the 2001 Particle Accelerator Conference, Chicago, Illinois (2002), the contents of which are incorporated herein by reference. See, also "Growth and Current Charities of a Stable Field Ion Emitter," K. Jousten et al., Ultramicroscope 26, pp. 301-312 (1988) and "Maskless, Resistless Ion Beam Lithography Process," Qing Ji, Ph.D. Dissertation, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley (2003), the contents of both of which are incorporated herein by reference. By limiting the number of emission sites where the gas is shared, a notable increase in current and current density from the remaining emitting sites occurs. Because of its long range in materials, the helium ion beam would traverse the entire sample 14 and exit from the back with great efficiency. The ion current registered in the detector 20 is read by the control computer 24. Thus, information on the ion signal as a function of deflected position of the beam can be gathered at the control computer 24 and displayed on an output screen 28 showing an image that reflects properties of the sample 14.

The detector portion of this embodiment of the invention is shown in Fig. 2 in more detail. The focused ion beam 30 impinges on the sample 14 that has been thinned in a predesignated area 32. Upon collisions with the lattice atoms of the sample 14, the helium ions undergo either large or small angle scattering. The former typically constitutes a dark field signal 34 while the latter typically constitutes a bright field signal 36. A pair of interchangeable apertures 38 and 40 are provided to select either the dark or bright field signal, respectively. The chosen component of the signal is collected in the ion detector 20 for recording in the control computer 24.

An alternate system is contemplated with little or no use of the computer beam control system. Two analog ramp generators, with one at a significantly higher frequency than the other, can both scan the helium ion beam and an analog driven CRT at the same time. The brightness of the CRT beam can be modulated by a signal from the transmission detector providing the equivalent of a gray scale (black and white) picture.

Yet another system can use a combination of computer control and ramp generators. In such a system, the computer detects the voltages of the ramp generators and creates a coherent picture by measuring these ramp generators and the output of the transmission detector.

The control of optical elements may be accomplished by manual means such as a knob or slider which, in turn, provides signals to certain high voltage supplies.

The scanning transmission ion microscope of the invention takes advantage of the unusually long range of helium ions in matter. The range can be 200 times longer than for a heavy ion such as gallium. Because the ion source used with the microscope disclosed herein can achieve sub-nanometer beam diameter, the microscope of the invention can achieve that which was previously possible only with an electron beam.

The collection of the transmitted (bright field) and/or scattered (dark field) ions can provide structural information about the sample. Further, the interaction dynamics of an ion beam with a sample material is different from interactions with an electron beam. There generally will be more effects from atomic centers and fewer effects from the electronic structure of the sample. This may be explained as nuclear contrast. In a bright field picture, dark pixels are the result of ions that interact with the atomic nuclei in the sample that are then scattered away from the detector or absorbed in the sample. Bright pixels in the image are typically the result of ions that are not scattered or absorbed by the atoms in the sample. In the case of a dark field picture, the contrast is reversed, or inverted, from the previous situation.

The system disclosed hereon will likely be simpler, smaller, and weigh less than a STEM or TEM because of the electrostatic optics. The electrostatic optics may be capable of accelerating, decelerating, collimating, focusing or deflecting an ion beam generated by an ion source for further processing within the optical column. The contrast in the displayed image will also be greater than for a STEM or TEM. The picture will have more elemental contrast and may be enhanced with a charge neutralizer.

The temperature of the sample may change the quality of the resulting image. The ion beam may cause atoms in the sample to vibrate thereby providing yet another contrast mechanism. Because crystal orientation may be important, a tilting sample holder may be used that may optionally provide an x-y motion. Picture contrast may also be affected by voltage and the comparison of pictures taken at different voltages can provide yet another contrast mechanism.

The energy loss of the ion beam at each position also carries information about the composition of the sample material. While a traditional STIM uses high energy (MEV) ion beams produced in accelerators, their resolution is nonetheless limited to about 50nm to about 100 nm. Those of ordinary skill in the art will appreciate that low energy ion scatter spectroscopy may be utilized to identify the elements in the sample.

Those skilled in the art will know or be able to ascertain using no more than routine experimentation, many equivalents to the embodiments and practices described herein. Accordingly, it will be understood that the invention is not to be limited to the embodiments disclosed herein, but is to be understood from the following claims, which are to be interpreted as broadly as allowed under the law.

What is claimed is:

1. Scanning transmission ion microscope comprising:

a gas field ion source to generate an ion beam;
a focusing electrostatic optical column to focus the ion beam;
a translation stage supporting a sample to receive the focused ion beam; and
a detector responsive to ions transmitted through the sample to generate a signal from which properties of the sample may be displayed.

2. The microscope of claim 1, further including a cold finger to vary sample temperature.

3. The microscope of claim 1, further including structure to maintain the microscope in a vacuum environment.

4. The microscope of claim 1, further including computer controlled placement of the ion beam on the sample.

5. The microscope of claim 1, further including a charge neutralizing electron beam to neutralize charge on an insulating sample.

6. The microscope of claim 1, wherein the ion beam energy is in the range of *1,000 V* to *1,000 keV.*

7. The microscope of claim 1, wherein the translation stage is configured for at least one of tilting and translation of the sample.

8. The microscope of claim 1, wherein the ion beam comprises helium ions.

9. The microscope of claim 1, wherein the ion beam has sub-nanometer beam diameter.

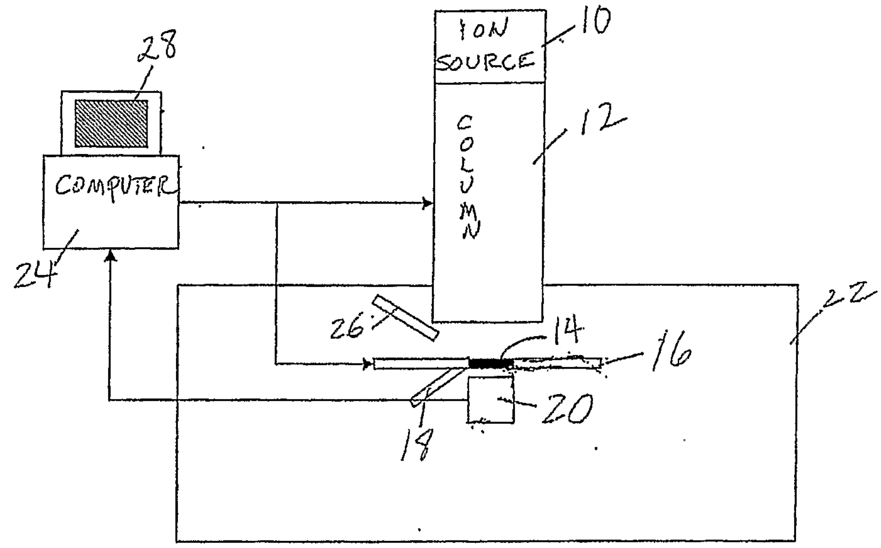
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Fig. 1

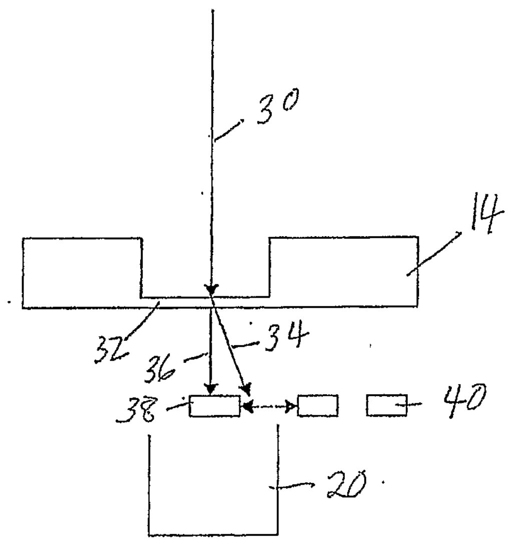
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Fig. 2