Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Nuclear Instruments and Methods in Physics Research B 231 (2005) 60–64
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Development of a secondary-electron ion-microscope for microbeam diagnostics

G. Garty *, G. Randers-Pehrson, D.J. Brenner

RARAF – Columbia University, 136 S. Broadway, Irvington, NY 10533, USA

Available online 17 March 2005

Abstract

We describe a novel secondary-electron ion microscope (SEIM), designed for diagnostics of the upcoming sub-micron Columbia University charged-particle microbeam. This secondary-electron ion microscope allows much higher resolutions, at higher single particle detection efficiencies, than previously available, for rapid and accurate diagnostics of sub-micron charged-particle beams. Based on ion electron-emission microscopy (IEEM) and photo-electron microscopy (PEM), the SEIM involves conversion of the incident projectiles on a secondary-electron emitting film. The ejected electrons are focused using a unipolar electrostatic lens and conical electrostatic mirror to form a magnified image on a microchannel plate (MCP). The flight path of the electrons includes two 45° bends; this "folded" geometry results in lower aberrations than a "straight" design, and enables efficient beam imaging down to 100 nm resolution with >50% single electron transfer efficiency.

PACS: 41.90.+e; 41.85.Ew; 87.64.Ee

Keywords: Emission microscopy; Microbeam diagnostics; Ion beam analysis; Spatial resolution

1. Introduction

The recent improvement in the spatial resolution of particle microprobes necessitates the development of novel methods for beam diagnostics. At Columbia University's Radiological Accelerator Research Facility (RARAF) the characterization of few-micron diameter proton and He^{++} microbeams (in air) is currently performed by scanning a thin knife-edge through the beam and monitoring the relative fractions of degraded and non-degraded particles [1]. However, as the microbeam diameter shrinks (a sub-micron beam is expected shortly) this technique becomes less and less reliable. With the implementation of the new laser ion source (LIS) [2], the need will arise to characterize a low flux beam of highly-charged, heavy

* Corresponding author.
E-mail address: gyg2101@columbia.edu (G. Garty).

0168-583X/$ - see front matter
doi:10.1016/j.nimb.2005.01.035

ions. In this case, both due to the short range and to the low beam flux, leading to prohibitively long measurement time, this technique becomes unusable.

The secondary-electron ion microscope (SEIM) described here represents a novel approach to beam diagnostics, enabling much higher resolutions, higher sensitivity and faster measurement times than previously possible. The SEIM design was inspired by the common technique of ion electron emission microscopy (IEEM) [3–5], used extensively in surface science [6,7] and in radiation damage studies [8]. The SEIM is based on conversion of the incident projectiles on a secondary electron emitting film. The ejected electrons are then focused to form a magnified image on an image intensified CCD. This compact folded design of the SEIM, wherein the electrons are bent by 45°, reflected off of a conical electrostatic mirror and bent by an additional 45°, is a novel one, developed by us, and allows much better performance than with a "straight" design, as described below.

The main requirements for the SEIM, as a practical method for beam monitoring are:

(1) *A resolution of 100–200 nm*. This is required for reasonable diagnostics of a sub-micron diameter beam.
(2) *Sensitivity to single projectile particles* (1–5 MeV protons, as well as highly-ionizing heavy ions). The particle detection efficiency must be high, to enable rapid beam diagnostics.
(3) *Compactness and simplicity of operation*. The SEIM is expected to be mounted on the microbeam end station before each irradiation.

2. SEIM design

The SEIM design is shown schematically in Fig. 1. The incident projectile particle generates one (or more) electrons in a thin secondary electron emitter (SEE). In our case this is the ion accelerator exit window which doubles as an entrance window to the SEIM. These electrons are accelerated and imaged, using an electrostatic unipotential aperture lens, onto a micro channel plate (MCP) coupled to a phosphor screen and a high resolution CCD camera. As the resolution of an MCP is about 50 μm, 500 times larger than the required 100 nm resolution, we need to obtain a magnification of ~500 with the electrostatic lens. At such high magnifications, aperture lenses suffer large spherical and chromatic aberrations [9].

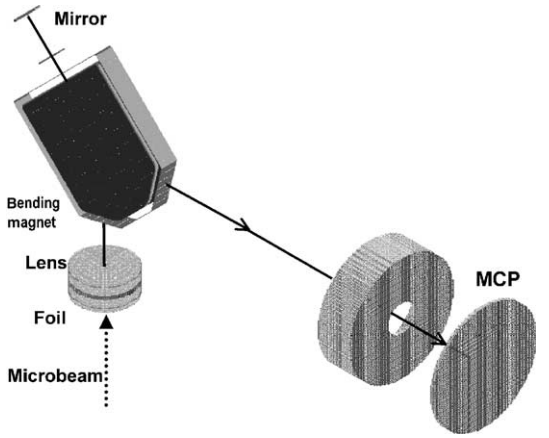

Fig. 1. Schematic layout of the secondary electron ion microscope. An ion microbeam impinges on a secondary electron emitter foil, generating secondary electrons. They are accelerated towards and focused by a unipolar aperture lens. En route to the MCP detector they are bent twice and reflected off of a conical mirror.

In order to overcome the chromatic and spherical aberrations, we have "folded" the electron path [10]: The electrons are bent by a 45° angle, using a double focusing sector magnet, they are then reflected by a conical electrostatic mirror and bent by an additional 45° by the same magnet before reaching the detector.

By using a specially designed, conical, electrostatic mirror it is possible to exactly compensate for the aberrations induced by the lens [10]. Furthermore, high energy electrons, which cannot be accurately focused, are sufficiently energetic to penetrate the mirror and are not reflected. This results in the loss of exactly that fraction of electrons which could not be easily focused and would degrade the obtained resolution. A similar spatial resolution for a straight design would require the use of a very small aperture in the beam path

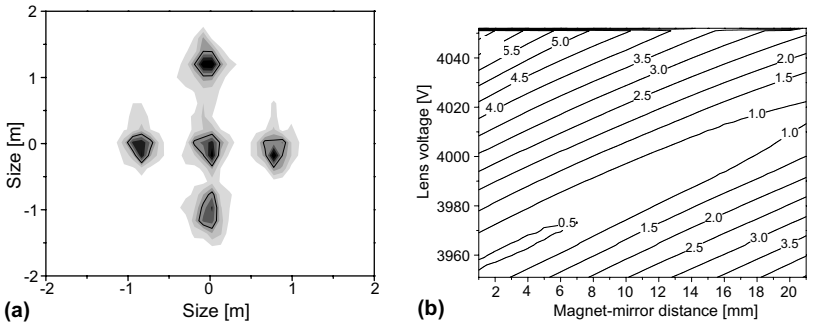

Fig. 2. (a) Simulated electron image of a 2 μm cross. The spot diameter is ~0.3 μm. This is the optimal spot in (b). (b) The dependence of the expected resolution (in microns) on the lens voltage (the acceleration voltage is 30 kV) and mirror placement (1.5 V biased 140° mirror).

and a typical electron transmission efficiency of ~1% (see Fig. 2 of [3]). For our design, the expected efficiency is 55–80%.

2.1. The simulations

We have performed extensive studies using SIMION (Scientific Instrument Services, Ringoes, NJ), in order to find the optimal configuration for the folded geometry.

As a benchmark for the various geometries we have taken a set of 5000 electrons having a cosine angular distribution and an energy distribution centered at 5 eV, with a high energy tail, as given in Fig. 5.14 of [11]. This is the energy spectrum for secondary electrons emitted from gold due to bombardment with 400 keV protons. These electrons were divided into five groups and flown from the center and four points of a 2 μm wide cross. The impingement coordinates on the MCP were then analyzed and the magnification and expected resolution (RMS of the center spot scaled by the magnification) calculated. Fig. 2(a) shows an example of the projection of these electrons onto the SEIM CCD plane. In this case the simulated resolution is 300 nm. By interfacing SimIon and Matlab (The MathWorks, Inc., MA), we have been able to implement a multidimensional search algorithm to find, automatically, the optimal SEIM operating parameters (mirror placement as well as the mirror and lens voltages), for given mirror opening angle. For example, Fig. 2(b) shows the dependence of the resolution on the lens voltage and on the mirror location, for a 150° mirror biased at −1.5 V with respect to the grounded electron emission foil.

Based on these simulations we have seen that the focusing can be adjusted, both by moving the mirror and by adjusting the lens voltage. We have also seen that the fact that our mirror could not be made absolutely sharp (it has a chamfer of 0.25 mm) has no detrimental effects on the SEIM resolution.

From these systematic studies we have found the "ideal" SEIM configuration, (a 150° mirror biased at 1.5 V with respect to the SEE film as well as the required lens voltage as a function of mirror placement), giving a single-electron resolution of 300 nm (see Fig. 2) and single electron transport efficiency of 55% (as compared to ~1% for an IEEM with the same resolution [3]). By raising the mirror bias to −5 V, a single electron transfer efficiency of 80% is reachable at a single-electron resolution of 500 nm. This efficiency does not include any other deficiencies in the detector system. We expect that this resolution will improve as the square root of the electron yield which is expected to be higher than unity for heavy/energetic ions, where the SEIM is needed most.

2.2. SEIM testing

We have built an "unfolded" SEIM, consisting of the electrostatic lens and the electron detector but without the magnet and mirror, in order to test the lens properties. For this version, simulations

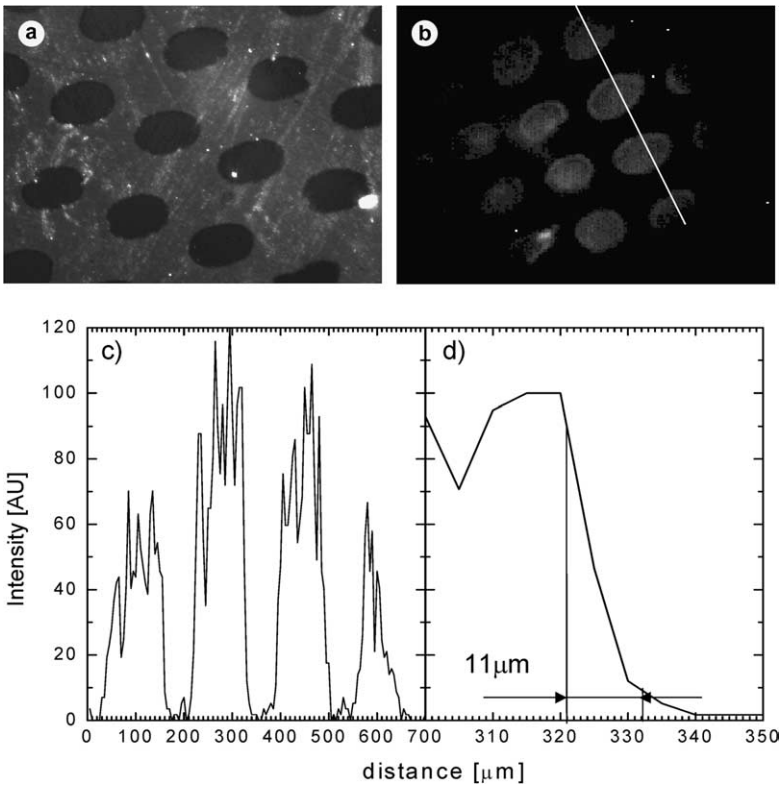

Fig. 3. (a) Photo of the aluminum pattern deposited on the SEE electrode, the pitch is 200 μm. The dark spots are thick aluminum deposits having high efficiency for photon-induced electron emission. (b) The pattern on (a) projected onto the MCP, the SEIM field of view for this magnification is 1 mm diameter. (c) A cross section of (b) along the line marked. (d) A close-up of the falling edge of the one of the peaks. The measured resolution (10–90%) is 11 μm.

have shown that both the resolution and magnification are 10–20 times inferior to the folded SEIM. It is however useful as a test bed for studying the lens properties, and the detector response, For testing and calibration purposes we replaced the SEE foil with a quartz window on which a micron scale pattern of aluminum was evaporated (see Fig. 3(a)). The pattern was illuminated with low intensity UV light and the resulting photoelectrons were imaged, similar to a photoelectron microscope (PEM [7]). The low intensity was necessary so that individual electron-induced pulses could be recorded, allowing us to overcome the large size of the light spots, generated on the phosphor by single-electron-induced avalanches in the MCP, as well as any non-uniform gain in the MCP. A sample image, based on ~200 000 electrons is shown in Fig. 3(b). The pattern can be easily seen. The low level background is primarily due to photon-induced electron emission from the thin aluminum layer used to ensure field uniformity near the emission electrode. Fig. 3(c) and (d) show a cross section of the image in Fig. 3(b). From Fig. 3(d), the width of the edge (10–90%) is about 11 μm, corresponding to a σ value of 4.3 μm. This is in good agreement with the simulated prediction of 4–5 μm for σ. The predicted magnification (16×) is also in good agreement with the measured 20×.

3. Conclusions

The SEIM is a novel tool for the diagnostics of sub-micron ion beams, based on the imaging of secondary electrons induced by single ions traversing a thin SEE film. Utilizing a novel folded

design, consisting of two 45° bends and a conical mirror, the SEIM is capable of 100 nm resolution with 55% electron transfer efficiency, much better than is attainable with other designs. Preliminary data on the lens performance agree well with our simulations. Once the SEIM construction is complete, it will be mounted onto the microbeam II endstation at RARAF on a pivot arm (see [1]) so that it can be conveniently brought above the beam for microbeam diagnostics and moved out of the way for biological irradiations.

Acknowledgments

The authors would like to acknowledge the continued support of the machine shop at the Center for Radiological Research and in particular Mr G.W. Johnson. We would also like to thank Dr G.F. Rempfer, of Portland State University, for sharing her vast experience with electrostatic mirrors. This work was supported by NIH grants EB002033-08 and CA49062-13.

References

[1] A.W. Bigelow, G.J. Ross, G. Randers-Pehrson, D.J. Brenner, Nucl. Instr. and Meth. B, these proceedings. doi:10.1016/j.nimb.2005.01.057.
[2] A.W. Bigelow, G. Randers-Pehrson, D.J. Brenner, Nucl. Instr. and Meth. B 210 (2003) 65.
[3] B.L. Doyle, G. Vizkelethy, D.S. Walsh, B. Senftinger, M. Mellon, Nucl. Instr. and Meth. B 158 (1999) 6.
[4] B.L. Doyle, D.S. Walsh, S.N. Renfrow, G. Vizkelethy, T. Schenkel, A.V. Hamaza, Nucl. Instr. and Meth B 181 (2001) 199.
[5] B.L. Doyle, Ion Photon Emission Microscope U.S. Patent 6,552,338, 22 April 2003.
[6] G.F. Rempfer, O.H. Griffith, Ultramicroscopy 47 (1992) 35.
[7] S. Günther, B. Kaulich, L. Gregoratti, M. Kiskinova, Prog. Surf. Sci. 70 (2002) 187.
[8] B.L. Doyle, F.D. McDaniel, G. Vizkelethy, P.E. Dodd, P. Rossi, D.S. Walsh, Nucl. Instr. and Meth B 210 (2003) 98.
[9] G.F. Rempfer, J. App. Phys. 57 (1985) 2385.
[10] G.F. Rempfer, J. App. Phys. 67 (1990) 6027.
[11] Secondary electron spectra from charged particle interactions. ICRU report 55, International commission on radiation units and measurements, Washinigton DC, 1996.