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NUCLEAR MICROPROBE FOR INTEGRATED CIRCUIT PROCESS INSPECTION

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Abstract

A nuclear microprobe with a minimum beam-spot diameter of less than 100 nm, intended for application to IC (integrated circuit) process inspection, has been designed and installed at Osaka University. An ultra high-vacuum sample-chamber with a three-axis goniometer stage and a toroidal electrostatic analyzer for medium energy ion scattering (MEIS) was combined with a short acceleration column for a focused ion beam. A liquid metal ion source (LMIS) for light metal ions such as Li+ or Be+ was mounted on the short column. A minimum beam spot-size of about 80 nm with a current of 30 pA was obtained for 400 keV Be++ LMIS. An energy resolution of $4 \times 10^{-3}$ (AE/E) for the toroidal analyzer gives rise to atomic resolution in RBS spectra for Si and GaAs. This system seems feasible for atomic-level in-depth analysis of localized surfaces and crystalline/disorder structures. The design concept and simulated focusing characteristics using beryllium and lithium liquid metal ion sources were compared with those of conventional microprobes. The feasibility of this microprobe to localized analysis of future IC process steps with a minimum feature size of less than a quarter micrometer was discussed.

Key Words: Nuclear microprobe, focused ion beam, Rutherford backscattering (RBS), channeling, lithium ion, beryllium ion, liquid metal ion source, surface analysis, medium energy ion scattering, integrated circuit (IC).

Introduction

Nuclear microprobes with focused MeV proton beams have successfully been applied to elemental mapping using particle induced X-ray emission (PIXE) in the field of biology, geology, and mineralogy [7,10,16]. In the meantime, increasing demands in microelectronics for localized analysis of designed structures required application of microprobe techniques using helium ion beams combined with Rutherford backscattering (RBS) to semiconductor process developments [14,15] with a lateral resolution of 1 micron or less and a depth resolution of 20 ~ 30 nanometers.

Secondary ion mass spectroscopy (SIMS) using a short-column focused ion beam (FIB) system with low-energy heavy ions such as gallium ions (Ga+), having a submicron lateral resolution, is also a useful technique for localized surface and in-depth analysis [3]. However, submicron SIMS has problems of sample destruction and difficulty in precise depth analysis arising from different etching rates of materials.

Sample sectioning by such a FIB system for cross sectional SEM (scanning electron microscopy) or TEM (transmission electron microscopy) measurement has recently been widely accepted as a powerful technique for IC investigation, though it is a destructive method [5]. Rutherford backscattering (RBS) using a high-energy light-ion microprobe is superior in nondestructive localized analysis to above mentioned competitive techniques [14,15]. A microprobe RBS measurement system with a goniometer stage can provide the localized and three-dimensional information concerning elemental composition, elemental distribution and crystallinity of the sample [14,15].

In recent years, a lateral resolution of 1...
micron or less with a depth resolution of a few tens of nanometers is achieved for RBS analysis using MeV or several hundred keV microbeam lines with H+ or He+ gaseous discharge ion sources [10,14,15]. However, the minimum feature size of integrated circuits (ICs) continues to shrink from micron down to submicron ranges. Figure 1 shows the minimum feature size of dynamic random access memories (DRAMs) as a function of DRAM capacity for each generation. The DRAM has been a technology driver for miniaturization in semiconductor technology for the last decade. 4 Mbit DRAMs with a feature size of 0.8 µm are now in the market. 16 Mbit DRAMs are already in the waiting list, though process and structural improvements are still required. 64 and 256 Mbit DRAMs with a feature size of 0.35 ~ 0.2 µm are targets in research and development. Furthermore, nanofabrication using electron beams and scanning tunneling microscope (STM) tips facilitates further miniaturization in fabrication [6,18]. Under such circumstances, structural and/or atomic imaging of modified structures is of great importance for process control.

Therefore, the lateral resolution of microprobes for RBS analysis of future IC processes or nanofabrication should be less than 100 nm. The lateral resolution of microprobe equipment is limited by the minimum beam spot size, which has to be increased when increased ion beam intensities are necessary for reasonable counting rates during measurement. To minimize the beam spot size of microprobes, it is necessary to use a focusing lens system with low aberration [16] and ion sources which have high brightness, small energy spread and small virtual source size such as gas field ion sources [1,12] or liquid metal ion sources (LMISs). Table 1 compares the characteristics of three types of ion sources. A duoplasma ion source used in our earlier study [14,15] has by 4 orders of magnitude lower brightness and 3 - 4 orders of magnitude larger source size than those of LMISs.

At present, H+ or He+ gas field ion sources [12] still have several problems for applying them to RBS equipment such as vibration from cooling system, difficulties in applying high voltages and their instabilities. Therefore, it seems the best choice to use LMIS with light ions such as lithium [2] or beryllium [1].

The lateral resolution of microprobes is also limited by vibration of equipment including a sample holder. Therefore, the whole equipment should be isolated from a floor vibration.

Focusing lens systems installed in most MeV microprobe systems are a combination of quadrupole magnets which have strong demagnification with relatively high aberrations, resulting in focusing limitation of 1 µm at 100 pA for H+ or He+ beams [16]. On the other hand, electrostatic einzel lenses are easily designed and

![Figure 1. Minimum feature size as a function of capacity for DRAMs from 1 Mbit to 1 Gigabit.](image)

<table>
<thead>
<tr>
<th>Species</th>
<th>Duoplasmatron</th>
<th>Field ion</th>
<th>LMIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brightness (A/cm²sr)</td>
<td>10²</td>
<td>10⁹</td>
<td>10⁶</td>
</tr>
<tr>
<td>Angular current density (µA/sr)</td>
<td>10³</td>
<td>1</td>
<td>10 - 60</td>
</tr>
<tr>
<td>Source size (nm)</td>
<td>5 x 10⁴ - 10⁵</td>
<td>1</td>
<td>30 - 40</td>
</tr>
<tr>
<td>Energy spread (eV)</td>
<td>4 ~ 20</td>
<td>1 ~ 2</td>
<td>5 ~ 50</td>
</tr>
</tbody>
</table>
assembled with less aberrations, though the demagnification is much less than that of the quadrupole magnet. The low demagnification of the electrostatic einzel lens limits the application to high energy ion beams. However, this lens system is appropriate for application to a medium energy range used in this study. Furthermore, such microprobe equipment for semiconductor process inspection will be placed in a clean room, where installation of conventional microbeam lines is difficult because of space limitation. Therefore, a short-column medium-energy microprobe-facility using electrostatic einzel lenses has great advantages over conventional microbeam system.

In this study, a compact nuclear microprobe with a LMIS and a toroidal analyzer has been designed and installed at Osaka University. The compact nuclear microprobe system has the size of conventional scanning electron microscopes and provides a beam spot-size of about 100 nm with a current of 100 pA. Such a system can provide not only structural images but also cross-sectional atomic images (i.e., in-depth imaging without sample sectioning) and meet the requirements of future IC process development and even nanofabrication with a feature size of several ten nanometers or less.

RBS Mapping and Tomography

Figure 2 shows the concept of total quantitative recording of RBS spectra for each of the scanning positions of a nuclear microprobe, the resulting RBS mapping at a certain depth, and RBS tomography at a certain cross-sectional plane [14,15]. The microprobe is raster-scanned over a sample surface (x-y plane). Each of the RBS spectra is stored in computer memory as a data block for a certain scanning position. The stored data blocks can be displayed or analyzed with appropriate software energy windows afterwards to produce both RBS mapping (at a certain depth or at a given species) and RBS tomography (at a certain cross-sectional plane). All the data necessary for analysis can be obtained by single measurement, which drastically reduces measuring time and, hence, radiation damage in a sample.

The lateral resolution of RBS mapping is determined by the probe diameter, while the in-depth resolution is determined by an energy loss factor and an energy resolution of detecting systems. Therefore, the lateral resolution ranges from 5 to 1000 nm, depending on the beam current. The resolution is feasible for future IC process inspection but not yet for lateral atomic

Figure 2. Schematic of RBS mapping and tomography with a scanning microbeam. Each of the RBS spectra corresponding to each of scanned positions is stored in computer memory. RBS mapping at a certain depth or at a given species and RBS tomography at a certain cross-sectional plane can be obtained with appropriate software energy windows.
scale imaging. However, a depth resolution in the range below 1 nm can be obtained by the use of the toroidal static energy analyzer used in this study, in which in-depth atomic level analysis is possible.

**Microprobe System Design**

Figure 3 shows the schematic diagram of a compact nuclear microprobe system with a 200 kV FIB accelerating column. The designed specification is summarized in Table 2. Lithium and/or beryllium (from Au/Si/Be eutectic alloy) LMISs are used for ion sources because of features such as small mass, high brightness, small virtual source size, and small energy spread. The focusing system consists of three stages of electrostatic lenses: a six-stage accelerator lens, a condenser lens and an objective lens. This focusing system can make the focusing column as compact as that in a conventional SEM system. The size of this system is less than 1/10 of conventional MeV microbeam lines, though it has a limitation in an acceleration voltage because of electrical break down of the electrostatic lenses. The maximum acceleration voltage of this column is designed to be 200 kV. Therefore, a maximum accelerating energy of 400 keV is achieved when doubly charged ions are selected by the ExB mass filter. A target chamber, mounted on a rubber mold coil spring, with a vacuum pressure lower than $5 \times 10^{-10}$ Torr has a sample holder mounted

![Microprobe System Diagram](image)

**Figure 3.** Schematic of a compact nuclear microprobe, including a toroidal analyzer (electrostatic prism) with a micro channel plate (MCP) detector. CL: condenser lens, OL: objective lens, LMIS: liquid metal ion source, AP: aperture, SSD: solid state detector, SE: secondary electron.

| **Table 2.** Specification of a compact nuclear microprobe installed at Osaka University. |
| **Focusing Column** |
| **Max. acceleration energy** | 200 kV |
| **Ion source** | LMIS (Li⁺, Be⁺) |
| **ExB mass filter resolution** | 9% (50 amu/charge) |
| **Focusing system** | 3 stage lenses electrostatic |
| **Focusing performance** | 50 nm / 50 pA |
| **Deflection field** | 500 µm x 500 µm |
| **Working distance** | 68 mm |

**Analyzer**

| **SSD** | surface barrier |
| **Electrostatic toroidal analyzer (0 - 400 keV)** |
| **Energy resolution** | $4 \times 10^{-3}$ (ΔE/E) |
| **Angular resolution** | 0.3° |
| **Scattering angle** | 32.5° - 109.5° |

**UHV Chamber**

| **Ultimate pressure** | < $5 \times 10^{-10}$ Torr |
| **Manipulator** | 6-axis goniometer 0.01° step |
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on a rigid six-axis goniometer, allowing channeling contrast measurement \([7,10,14,15]\). Vibration of the sample holder against the incident beam should be reduced to less than the spot size of the beam. The vibration of this work chamber is reduced to less than \(1/200\) of the floor vibration (vibration frequency > 5 Hz) by the use of rubber mold coil spring. Thus, if the floor vibration is around \(1 \mu m\), the vibration of the sample holder against the incident beam is less than \(5 \text{ nm}\). Three rotational axes are controlled by stepping motors with an accuracy of \(0.01^\circ\). Secondary electron images, useful for determining the position on a sample, are obtained from a scintillator by scanning a microprobe over the sample by electrostatic deflectors. For RBS analysis, this system has a solid state detector (SSD) and a toroidal electrostatic analyzer with a position sensitive detector. An energy resolution \((\Delta E)\) ratio against the incoming ion energy \((E)\) of the toroidal analyzer is \(4 \times 10^{-3} \ (\Delta E/E)\). This high energy resolution of the toroidal analyzer allows precise measurement of medium-energy RBS, resulting in a depth scale of nanometers \([9]\). The energy resolution of \(4 \times 10^{-3} \ (\Delta E/E)\) corresponds to depth resolutions of 0.21, 0.29, and 0.32 nm for Au, GaAs, and Si, provided that a \(\text{Li}^+\) probe at 100 keV and a scattering angle of \(90^\circ\) are used.

The toroidal analyzer, rotatable around a sample, can detect scattered ions with angles from \(32.5^\circ\) to \(109.5^\circ\) (against the incident beam) with an angular resolution of \(0.3^\circ\). RBS signals from the SSD or toroidal analyzer are stored and processed by a linked computer. The use of a microbeam can provide information concerning lateral mapping of elements as well as the depth distributions within the near-surface regions of samples. Non-destructive three-dimensional analysis can be performed by scanning the microprobe over a sample with computed signals as shown in Fig. 2 \([14,15]\).

Lithium and beryllium ions have following characteristics as compared with hydrogen and helium ions; a) heavier masses, b) larger scattering cross section and c) higher electronic stopping power. Light ions should be used in comparison to target atoms for RBS analysis. Figure 4 shows the calculated scattering cross section \([4]\) as a function of target atomic number for H, He, Li and Be ions. \(100 \text{ keV} \text{Li}^+\) or \(\text{Be}^+\) probe ions yield a factor of 900 - 1600 larger scattering cross section in Si than 2 MeV \(\text{He}^+\). A total probe dose per measurement can be decreased because of larger scattering cross sections. For light target species, elastic recoil detection analysis (ERDA) with large cross sections \([10]\) can be applied as well. Figure 5 shows the calculated electronic stopping power \([19]\) as a function of energy for H, He, Li and Be ions in Si. Be ions have a higher electronic stopping power at the same energies, and, hence, they have higher depth resolution.

![Figure 4](image1.png)

**Figure 4.** Calculated scattering cross section as a function of target atomic number for H, He, Li and Be ions.

![Figure 5](image2.png)

**Figure 5.** Calculated electronic stopping power as a function of energy for H, He, Li and Be ions in Si.
Thus, the compact nuclear microprobe with a short FIB accelerating column system with LMISs can provide higher RBS scattering yield with good depth resolution when combined with a toroidal analyzer.

**Beam Optics Simulation**

Figure 6 shows the schematic of the system consisting of three-stage lenses (acceleration, condenser, and objective lenses), an ExB filter, and a toroidal electrostatic analyzer. Ion beams which are extracted from the LMIS are accelerated up to 200 kV by the accelerator lens and then are focused initially on the crossover point at the center of the ExB mass filter by the condenser lens. If the crossover point is not at the center of the ExB mass filter, astigmatism induced by the mass filter due to the beam energy spread is not negligible. The ion beam is then focused on a sample by the objective lens. The toroidal electrostatic analyzer in Fig. 6 is illustrated schematically. The actual location of the toroidal analyzer is illustrated in Fig. 3. A special care is taken to obtain a long working distance between the objective lens and the target. The distance allows the installation of an analysis system, consisting of a secondary electron detector, a SSD, and a toroidal analyzer. The focusing performance of this system using beryllium LMIS was evaluated under a condition of 68 mm working distance.

Aberrations of the focusing lens system shown in Fig. 3 can be calculated by a finite element method [11]. Table 3 shows the spherical and chromatic aberration coefficients for accelerator, condenser, and objective lenses. Focusing characteristics can be further estimated using calculated aberrations and ion source specifications [17].

Figure 7 shows the calculated beam spot diameter as a function of beam current for a Li+ LMIS, provided that the source size, the angular current density, and the energy spread of the Li+ LMIS are 25 nm, 20 μA/sr, and 5 - 15 eV. Microprobes with a beam spot-size of about 100 nm with a current of 100 pA can be obtained at 200 keV. A minimum beam spot-size of 10 nm with a current of 10 pA is estimated for 200 keV Li+ beams.

Figures 8 and 9 show the calculated beam spot diameter as a function of beam current for a Be+ and a Be++ LMIS. The source size, the angular current density, and the energy spread of

| Table 3. Optical coefficients of the focusing column. Cs: Spherical aberration coefficient, Cc: Chromatic aberration coefficient, M: Magnification. |
| --- | --- | --- |
| Accelerator Lens | 39500 | 3090 | -1.09 |
| Condenser Lens | 2110000 | 759 | 0.494 |
| Objective Lens | 114000 | 244 | 0.351 |
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Figure 7. Calculated beam spot diameter as a function of current for a 100 keV and a 200 keV Li+ LMIS obtained using calculated aberrations.

The Be+ and Be++ LMISs are obtained from published data [1] and are 25 nm, 6 µA/sr, and 10 eV, and 25 nm, 15 µA/sr, and 8 eV, respectively. Singly-charged beryllium ion-beams provide a current of 100 pA with a beam spot-size of 600 and 1600 nm at 200 and 100 keV, respectively, while doubly-charged beryllium ion-beams provide smaller beam spot-sizes because of the higher angular current density and lower energy spread. Be++ microprobes with a beam spot-size of about 100 nm with a current of 40 - 80 pA are estimated at 200 - 400 keV. A minimum beam spot-size of 10 nm with a beam current of 2 pA is estimated for 200 keV Be++ beams.

Thus, the lithium LMIS is more suitable for obtaining smaller spot-size with high current.

Although the dimensions of the focusing column are shown in Fig. 6, it is possible to change the position of the condenser lens by a minor modification of the electrode shape, without changing other parts and the crossover point. Figure 10 shows the Be++ beam current as a function of condenser lens position, under a condition of 50 nm beam diameter. Thus, current densities can be controlled by changing condenser lens position.

Figure 8. Calculated beam spot diameter as a function of beam current for Be+ LMIS.

Figure 9. Calculated beam spot diameter as a function of beam current for Be++ LMIS.
Figure 10. Calculated beam current as a function of condenser lens (CL) position under a condition of 50 nm beam diameter. The reference position (0) is the CL position in Fig. 6 and the negative sign corresponds to movement down stream.

Beam Spot-Size Evaluation and Discussion

Figure 11 shows the secondary electron image of 1 µm latex balls on a nickel mesh obtained with a 400 keV Be\textsuperscript{++} focused ion beam. The beam spot size can be estimated to be about 80 nm in this figure. The measured probe current was about 30 pA. Thus the performance of this focusing column is almost the same with the simulated one, though the system is not yet fully optimized.

The estimated and measured probe beam characteristics of this system can easily meet the requirement of the minimum feature size of future Gigabit-memory ICs. Though a higher current density microprobe allows a rapid measurement, it can easily damage semiconductor devices for long time irradiation \cite{8,13}. Feasibility of RBS mapping and channeling contrast measurement with such a small spot diameter must be further tested.

These probe beam characteristics cannot meet the requirements of the atomic surface imaging. However, structural image mapping, combined with micro RBS and channeling contrast techniques, with lateral and in-depth resolutions of 10 and 0.2 nm, respectively, would provide indispensable information for future nanofabrication process development.

Summary

A compact nuclear microprobe system with a LMIS for IC process inspection has been designed and constructed. The system size is almost comparable with a conventional SEM system and can be easily installed in a clean room for semiconductor processing. A beam spot diameter of 10 - 50 nm with a current of 10 - 50 pA is estimated by a calculation of optical properties for 200 keV Li\textsuperscript{+} LMIS. A beam spot diameter of 80 nm with a current of 30 pA is obtained for 400 keV Be\textsuperscript{++}, the value of which is in good agreement with simulated one. The estimated lateral and in-depth resolutions of 10 and 0.2 nm, respectively, are feasible for IC process inspection with a minimum feature size of future Gigabit-memory ICs and even for atomic level analysis and structural mapping of localized crystalline/disorder structures and surfaces.

Acknowledgments

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References


Discussion with Reviewers

D.N. Jamieson: The large scattering cross sections will be an advantage here, however a large area detector may also be necessary. What is the solid angle of the toroidal analyzer?

Authors: It is about 4.6 msr.

K. Traxel: Do you really intend to change current densities by changing the condenser lens position?

Authors: Yes, only in the initial stage, we would like to optimize the lens position.

K. Traxel: Why do you make secondary electron images from a scintillator? You normally use the fluorescence on the scintillator to directly observe the beam spot.

Authors: Direct observation of the beam spot by the fluorescence on the scintillator is only possible using an optical microscope when the beam spot is larger than 1 µm. In this study, the beam spot size is less than 100 nm, and hence a secondary electron image using the scintillator is indispensable for beam spot-size evaluation.

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