MEIS-K120 Application Note
Table of Contents

Introductions

1. Medium Energy Ion Scattering Spectroscopy (MEIS)
   1.1 Kinetic Factor
   1.2 Scattering Cross Section
   1.3 Stopping Power
   1.4 Channeling
   1.5 Time-of-Flight Medium Energy Ion Scattering Spectroscopy (TOF-MEIS)

2. MEIS-K120

3. Comparison of surface analysis techniques

4. Comparison of equipments possible for compositional depth profile

Applications

1. Ultra Thin Films
   1.1. Gate oxide (SiO₂)
   1.2. Compositional depth profile of High-k material (HfO₂)

2. Composition and the crystalinity of Ultra Shallow Junction (USJ)
   2.1. Qualitative and quantitative analysis
   2.2. Crystalinity

3. Compliment for SIMS

4 Nano particles
   4.1. Quantum dots
   4.2. Conformal doping profile of FinFET

5. Pattern analysis

6. Strain profile*

7. Light element analysis by TOF-ERDA.*

*Although these results are from the other equipments, MEIS-K120 is capable of applying this filed.
1. Medium Energy Ion Scattering Spectroscopy (MEIS)

Medium Energy Ion Scattering spectroscopy (MEIS) is the non-destructive technique that analyzes the compositional depth profile of the sample with the atomic depth resolution (3 Å) using medium energy (~100 keV) ion. When a 100 keV He\(^+\) ion impinges on the sample, the incident ion is scattered by one of the target nuclei of the sample. The energy of scattered ion is decreased depending on the target elements and the depth. The detector measures the scattered ion energy with the \(10^{-3}\) energy resolution \((\Delta E/E)\), resulting in the compositional depth profile of the sample with the 3 Å depth resolution. In addition, atomic structure of crystal array is analyzed by a channeling method. MEIS is an excellent tool for the analysis of the surface and the interface of the ultra thin film and nano-materials of 5~200 Å scale.

![MEIS Spectra Diagram](image)

* \(K(m_1/m_2, q) = E_2/E_0\) : Qualitative analysis of the elements
* \(ds/d\Omega\) : Quantitative analysis of the elements
* \(dE/dx\) : Compositional depth profile with 3 Å depth resolution
* Channeling and blocking : structure analysis of the crystal

Figure 1. The schematic diagram of MEIS spectra from the sample. The incident ion is scattered by 2 elements in the sample, 2 peaks are represented in the MEIS spectra. The scattered ion energy is the incident ion energy times the kinematic factor of each element \((K_1\) and \(K_2\)). The thickness or the depth of each element is presented as the peak width in the spectrum \((\Delta E = \text{thickness} \times \text{stopping power})\). The peak height is determined by the differential cross section and the amount of each element.
1-1. Kinematic Factor – Qualitative analysis

As medium energy He⁺ gets to the sample, the projectile ion \( M_1 \) collides with one of the target atoms \( M_2 \) of the sample, and the energy of the ion is decreased by its kinematic factor \( K \); depending on the mass ratio \( M_1 / M_2 \) of the projectile ion \( M_1 \) to the target atom \( M_2 \) and the scattering angle \( \theta \). If the energy of scattered ion is measured, the mass of target nucleus is calculated, resulting in the quantitative analysis of the elements composing the sample.

![Figure 2](image)

**Figure 2.** The binary collision of the projectile of ion with the target atom. The projectile ion of mass \( M_1 \) hits the stationary target atom of \( M_2 \) with velocity \( v_1 \) and the incident energy \( E_0 \). It is scattered to the scattering angle \( \theta \) with the velocity \( v_1' \) and the scattering energy \( E_1 \) (KE₂). Scattering angle depends on the impact parameter in addition to the energy and potential. After a collision, stationary target atom recoiled with a velocity \( v_2 \) and the kinetic energy \( E_2 \).

\[
K = \frac{E_{\text{scattered}}}{E_{\text{incident}}} = \frac{\left[ 1 - \left( \frac{M_1}{M_2} \right)^2 \sin^2 \theta \right]^{1/2} + (M_1 / M_2) \cos \theta}{1 + M_1 / M_2}
\]  

\( E : \) ion energy \hspace{1cm} \( M_1 : \) Mass of incident ion  
\( \theta : \) Scattering angle \hspace{1cm} \( M_2 : \) Mass of target atom
1-2. Scattering Cross Section – Quantitative analysis

How many ions are scattered by one target atom (M_2) at the scattering angle θ when one incident ion impinges on the unit area? This is the concept of the differential scattering cross section. The Rutherford cross-section for backscattering is given in the laboratory system by

\[
\frac{d\sigma_R}{d\Omega} = \frac{Z_1 Z_2 e^2}{4E} \left( \frac{1}{\sin^2 \theta} \right)^2 \left( 1 - \left( \frac{M_1 \sin \theta}{M_2} \right)^2 \right) \left( \frac{1 - \cos \theta}{\sin \theta} \right)^2
\]

(2)

\( E \): ion energy \quad \( M_1 \): Mass of incident ion \quad \( \theta \): Scattering angle \quad \( M_2 \): Mass of target atom

\( Z_1 \): Atomic number of incident ion \quad \( Z_2 \): Atomic number of target atom \quad \( \Omega \): Solid angle of detector

It is calculated by the concept of the elastic collision of 2 charged particles (incident ion and the target nucleus). Experimental measurements indicate that actual cross-sections is different from Rutherford at the medium energy around 100 keV. This difference comes from partial screening of the nuclear charges by the electron shells surrounding both nuclei. This screening is taken into account by several correction factors F.

\[
\frac{d\sigma}{d\Omega} = F \frac{d\sigma_R}{d\Omega}
\]

(3)

The real number of the scattered particles that are detected at detector is proportional to the solid angle of detectors (dΩ), the number of incident ions (Q), and the areal density of the sample (Nt). If the number of scattered particles is measured with the known solid angle of detector and the number of incident ion, the areal density (Nt) is calculated without reference materials.

\[
A = \frac{d\sigma}{d\Omega} \Omega Q Nt
\]

(4)

\( A \): Total number of scattered ions \quad \frac{d\sigma}{d\Omega} \quad \text{Differential scattering cross section}

\( Q \): Total number of incident ions \quad N \quad \text{Number density of target}

\( t \): Thickness of sample
1-3. Stopping Power – Depth profile

The energy of the incident ion is decreased as proportional to its path length inside the sample even though it doesn’t collide with the target nucleus. This energy loss arises from the electrons or the surrounding nuclei when it passes through the empty area (the volume except nuclei) of the sample. The scattered energy of the target elements deep in the sample is different from that of the same elements on the sample surface. The energy loss ($\Delta E$) caused by unit length ($\Delta x$) in the medium is called the Stopping power (S). It is related to the energy and the mass of the incident ion, the composition and areal density of the sample. The scattered energy spectrum can be converted to the compositional depth profile by using the stopping power in addition to the kinematic factor and differential cross section.

The medium energy region (~120 keV) feels larger stopping power than other energy regions when the incident ion passes through the sample. As a result, the scattered energy distribution is very sensitive to the thickness of the sample or the depth distribution of the elements at this medium energy region.

\[
\lim_{\Delta x \to 0} \frac{\Delta E}{\Delta x} = \frac{dE}{dX} \quad \text{Stopping}
\]

\[
E(x) = E_0 - \int_0^x \frac{dE}{dX} \, dx
\]

\[
\varepsilon = \frac{1}{N} \frac{dE}{dX} = \frac{K}{\cos \theta_1} \varepsilon_{in} + \frac{K}{\cos \theta_2} \varepsilon_{out}
\]

$\Delta E \approx 300$ eV/nm Si

Figure 3. The scattering energy of one species of the sample depends on the position (depth) that the species exists. The ion scattered by the surface target atom (green) has the scattering energy of $KE_0$. On the other hand, the ion scattered by the target atom that exists at the deeper region (blue), loses the energy more by the stopping power than that does by the surface atom.
1-4. Channeling – Structure analysis

Figure 4. The random and the channeling condition of MEIS experiment and the resulting MEIS spectra.

If the collimated incident ion beam is aligned with the crystal array, the cone shape shadow is formed behind the 1st atom of the crystal array. The incident ions cannot meet with the target nuclei in this shadow cone. As a result, the collision probability of the incident ions with the sample elements is largely reduced. This condition is called “channeling” or “aligned”. In this condition, the incident ions are scattered mainly by misaligned atoms. This technique can be applied to the evaluation of the activation ratio for the semiconductor, which shows the ratio between the aligned and the misaligned dopants in the silicon lattice.
To largely reduce the scattering yield by aligned atoms, the scattering angle is also aligned as well as the incident angle. This condition is called “double aligned”, and the blocking cone that looks like the shadow cone is formed in the path of scattering.

Figure 5. The shadow and the blocking cone at the double aligned condition of MEIS experiment.

If the MEIS spectra are measured as a function of the scattering angle keeping with the incident angle of the incident ion, the yield is the lowest at the double align condition, and is increasing as the angle became far from the double align condition. This yield is plotted as a function of the scattering angle, results in the blocking curve. The blocking dip depends on the lattice constants related to the scattering direction.

Figure 6. The blocking dip shifts depending on the lattice parameter.

Blocking dip is shifted when the lattice constants are changed by the strain. Strain at the surface or interface is measured using this method.
1-5. Time-of-Flight Medium Energy Ion Scattering Spectroscopy (TOF-MEIS)

Time-of-Flight MEIS (TOF-MEIS) uses TOF as an analyzer that determines the energy of scattered ions by measuring the flight time of particles. To use TOF analyzer instead of conventional electrostatic analyzer (ESA), short pulsed ion beam must be used, TOF-MEIS uses pulsed ion beam of about 100 keV shorter than sub ns.

* Time-of-Flight (TOF): Particles that have different kinetic energy reach a detector at different times for the same flight length in a vacuum. If the flight length is known, the flight time of scattered particle is converted to the kinetic energy of it.

Medium energy ions around 100 keV He⁺ are easily neutralized when they hit the sample or are scattered. They have the same kinetic energy but they do not have charges, they could not be detected by ESA analyzer. Because of this reason, to analyze the typical MEIS (ESA-MEIS) spectrum, the neutralization effect corrections must be added. However, TOF-MEIS detects the scattered particles without the loss of neutralized particles, because TOF analyzer measures the time that the particle reaches the detector regardless of its charges. TOF-MEIS analyze the compositional depth profile of the sample without correction.
2. MEIS-K120

- **Absolute quantification**
  MEIS-K120 adopts the TOF analyzer, it provides **absolute compositional profile** of the sample.

- **Semiconductor test pattern analysis with 10 μm size focused ion beam**
  MEIS-K120 focuses 100 keV He⁺ ion beam, the size of 10 μm, on the sample. The manipulator freely moves to the target position with a help of high performance microscope or secondary electron (SE) image. With 10 μm probe beam, MEIS-K120 analyzes the compositional depth profile at about 30 μm size samples such as semiconductor test pattern. This measurement enables a compositional depth profile or the activation ratio of semiconductor with a 10 μm spatial resolution and 3 Å depth resolution.

*Figure 8. The schematic diagram of the MEIS-K120 beam line.*
● Short analysis time.
  : MEIS-K120 reduces the measurement time to 10 min for point analysis of HfO$_2$. It is achieved by highly bright ion source, the best ion beam alignment, and large area position sensitive detector. In addition, Software including auto fitting function, parallel algorithm helps analysis fast and convenient.

● Adequate size for the analytical laboratory.
  : 3 m (w) \times 3 m (d) \times 2.5 m (h).

![Figure 9. The required size of the space for the MEIS-K120 installation.](image)

● Convenience
  : All operation including the equipment condition monitoring is possible at the operation PC. The S/W provides the simple and intuitive interface.
3. Comparison of surface analysis techniques

This graph represents the depth resolution and detection limit of several surface analysis tools when the compositional depth profile is measured by them.

Figure 10. The depth resolution and the detection limit of various surface analysis techniques.

Among surface analysis techniques, the analysis tool using ion beam sputtering such as XPS and SIMS destructs the sample, the results are interfered by matrix. In addition, the ion beam mixing happens during sputtering process, so the depth resolution is lowered. Transmission Electron Microscope (TEM) and Atom probe have difficulties to represent the whole sample because they analyze very small local area although they are the best for depth resolution. They also have weakness of ion beam damage and contamination during the sample preparation. MEIS has a good detection limit as well as non-destructive and the best for depth resolution as 3 Å.
4. Comparison of properties of several instruments

**Table 1. The comparison of equipments for surface analysis**

<table>
<thead>
<tr>
<th></th>
<th>HRBS</th>
<th>Atom probe</th>
<th>SSRM</th>
<th>Shallow Probe</th>
<th>AR-XPS</th>
<th>MEIS-K120</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measurement field</strong></td>
<td>- Compositional depth profile of film</td>
<td>- Compositional depth profile</td>
<td>- 2D imaging of carriers</td>
<td>- Compositional depth profile,</td>
<td>- Quantification Bond character of compounds</td>
<td>- Compositional depth profile</td>
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<td></td>
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<td></td>
<td></td>
<td>- Crystalinity of film and nanoparticles</td>
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<tr>
<td><strong>Measurable depth range</strong></td>
<td>~500Å</td>
<td>Depend on material &amp; analysis condition</td>
<td>No limit</td>
<td>0-7000Å</td>
<td>&lt;100Å</td>
<td>No limit with sputtering</td>
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<td></td>
<td>~200Å</td>
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<tr>
<td><strong>Depth resolution</strong></td>
<td>2 Å</td>
<td>1-3Å</td>
<td>(100Å)</td>
<td>&lt; 10 Å</td>
<td>3 Å</td>
<td></td>
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<tr>
<td><strong>Lateral resolution</strong></td>
<td>1 mm ~5 μm</td>
<td>0.3-0.5 nm</td>
<td>10 nm</td>
<td>50 μm</td>
<td>~ μm</td>
<td>10 μm</td>
</tr>
<tr>
<td><strong>Detection limit</strong></td>
<td>100 ppm (As)</td>
<td>10 ppm</td>
<td>10^{15}-10^{20} carriers /cm^{2}</td>
<td>100 at% ~10 ppm</td>
<td>0.1%</td>
<td>&lt;0.1% (As)</td>
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<tr>
<td><strong>Application filed</strong></td>
<td>-High-k</td>
<td>-Super-alloys</td>
<td>-Dopant distribution</td>
<td>-High-k</td>
<td>-Thin film</td>
<td>-High-k</td>
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<td></td>
<td>- Dopant profile</td>
<td>-Grain boundary</td>
<td>-p/n Junction interface</td>
<td>-Dopant profile</td>
<td>-Metal</td>
<td>-Dopant profile</td>
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<td></td>
<td>- Activation ratio</td>
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<td>-Semi-conductor</td>
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<td>nano-particle</td>
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<td><strong>Sample destruction and damage</strong></td>
<td>Non-destructive</td>
<td>Destructive</td>
<td>Destructive</td>
<td>Non-destructive</td>
<td>Non-destructive /Destructive</td>
<td>Non-destructive</td>
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<tr>
<td></td>
<td>Little Ion beam damage</td>
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<td>(sputter)</td>
<td>Scant ion beam damage (less than HRBS)</td>
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<td><strong>Light element analysis</strong></td>
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<td>H, B, C</td>
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<td>( Possible theoretically)</td>
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* Under Development
Application 1: Ultra Thin Film

Recently, the sizes of semiconductor devices have been reduced to sub nm. The depth as well as the width of the components of these devices such as channels, oxides, and dielectric layers also have decreased to comparably matching size. MEIS-K120 analyzes compositional depth profile of any kinds of ultra thin film from sub Å to hundreds Å depth with a 3 Å depth resolution.

1-1. Gate oxide (SiO₂)

SiO₂ is the traditional gate oxide with a perfect stoichiometry (Si : O = 1 : 2). SiO₂ of about 100 Å is measured and analyzed by MEIS-K120. (Figure 11) 100 keV He⁺ is used for measurement with the 45° incident angle and 90° scattering angle.

Figure 11. (a) The structure of the SiO₂ of about 100 Å made by plasma enhanced chemical vapor deposition (PECVD) on Si. (b) MEIS spectrum of SiO₂ on Si (c) The depth profile of Si and O in the 100 Å SiO₂/Si.
1-2. Compositional depth profile of High-k material (HfO₂)

As thickness of gate oxide (SiO₂) of semiconductor has been reduced to sub nm, the leakage current has arisen. To reduce this leakage current of thin gate oxide (SiO₂), several kinds of High-k materials such as HfO₂, TaO₂, TiO₂ are suggested. MEIS-K120 measures the compositional depth profile of HfO₂ thin films of thickness from 8.3 Å to 37.8 Å. As shown in the figure 12, 5 Å difference of HfO₂ in depth is properly resolved.

Figure 12. (a) the structure of HfO₂/SiO₂/Si sample. (b) MEIS spectrum of 6 hafnium oxide (HfO₂) samples (8.3~37.8 Å). (c) The depth profile of Hafnium of the HfO₂/SiO₂/Si sample. This sample is made at the Korea Research Institute of Standards and Science (KRISS) and is qualified by XPS with TEM.¹

Application 2: Composition and the crystallinity of Ultra Shallow Junction (USJ)

2-1. Qualitative and quantitative analysis

To make a source, drain, and the channel of the semiconductors, the carriers must be added to Si substrate. Usually, carriers such as As and B are added to Si by being implanted to substrate and then annealed. During annealing, the implanted carriers in the Si substrate show a compositional depth distribution by a function of the ion dose and the energy that is used for implantation, and the annealing condition.

Figure 13 shows 2 kinds of MEIS-K120 spectra of As doped Si and the depth profile of As with a 3 Å depth resolution – the black line is the spectrum of As implanted to Si before annealing and the other one is an annealed sample after being implanted. As shown in Figure 13 (b) and (c), implanted As (black line) mainly exists at about 50~150 Å before annealing. On the other hand, As (red line) spread to broad depth range over 200 Å, and is concentrated on the 15-30 Å depth region after annealing. Like this example, the compositional depth profile of dopant in the substrate for depth under 200 Å like USJ is one of the best application fields of MEIS-K120.

Figure 13. (a) The structure of As doped Si. (b) MEIS spectra and (c) the depth profile of As. This sample is made by implanting $1 \times 10^{15}$ As with 8 kV, and annealed. It is fabricated at National Nano Fab Center of Korea.
2-2. Crystalinity (Under Development)

The random spectra of MEIS show the compositional depth profile of the sample. At the channeling condition of the MEIS, which means that the ion beam is aligned to the lattice of the crystal, the scattered particles mainly come from the disorder of the crystal. If the semiconductor with carriers is measured by both random and channeling methods, random spectra show the total compositional depth profile of the carrier, and the channeling spectra show that of inactivated ones. By using this difference, the amount or the ratio of the aligned carriers among the total dopant is analyzed. In semiconductor, the ratio of the aligned quantity to the total implanted dopant is called “activation ratio”. In this way, MEIS analyzes the activation ratio of dopant as well as the compositional depth profile.² (Introduction 1-4)

![Diagram of activated and inactivated dopants in Si crystal](image)

Figure 14. The activated and inactivated dopants in the Si crystal.

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The Figure 15 shows (a) the random and the channeling spectra of the As doped to Si after annealing and (b) the depth profile of the As and the activation ratio of that. As shown in the Figure 15 (b), As is spread to about 270 Å and a large amount of activated As is concentrated on the depth 15~20 Å.

Through annealing process, the As implanted dopant is redistributed and aligned to Si lattice. The annealing condition is important because the depth profile and the activation ratio depend on the annealing condition, and influence the performance of semiconductor devices. Sometimes, the depth profile and the activation ratio of the carriers or the performance of semiconductor devices vary with the facilities that are used for annealing, even though they are operated with the same parameters. It is supposed that this difference comes from the time differences and the conditions of each equipment. MEIS-K120 is capable of finding the optimum conditions of each equipment as well as monitoring the performance variance of each annealing facility by analyzing the activation ratio of the dopant as well as the compositional depth profile of the semiconductors.
Application 3 : Compliment for SIMS.

Secondary Ion Mass Spectroscopy (SIMS) measures the mass and the amount of the secondary ions by ion beam sputtering. When the ion beam sputters the sample, the element that is included in the sample is ionized. The amount of secondary ions varies with the matrix (matrix effect). As a result, the quantity of the element in the sample is distorted especially at the position where the different matrices are encountered such as surface and the interface. In addition, the ion beam pushes some of the elements of the sample to the deeper region or mixes elements of upper region with elements of deeper region (ion beam mixing effect), it makes the depth resolution low. MEIS-K120 analyzes the sample without destruction, it does not distort quantity of the elements in the sample and is powerful complimentary tool for SIMS analysis of surface and the interface.

Figure 16. (a) The MEIS spectra of $1 \times 10^{15}$ As atoms/cm$^2$ implanted Si by 8 kV and (b) the depth profile of As analyzed by MEIS (blue line) and SIMS (red line). In the MEIS experiment, 69.5 keV He$^+$ was used as a probe beam, and the scattering angle was 135$^\circ$. Total dose of As was resulted as $1.0 \times 10^{15}$ by MEIS and the and $1.2 \times 10^{15}$ atoms/cm$^2$ by SIMS.
Application 4: Nano particles (Under Development)

The sizes and the compositional profiles of the sub nm nano particles are measured and analyzed by MEIS-K120 with the help of 3D simulation\(^3\). When the medium energy ion beam hits the sample, the energy loss occurs according to the ion beam path in the sample. In the nano particles, the ion beam path varies with sizes or shapes of particles. This difference in energy loss makes MEIS possible to analyze the size and the compositional depth profile of nano particles.

![3D MEIS simulation for various particle shape.](image)

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4-1. Quantum dots

The CdSe quantum dot emits UV/Vis light and has been widely used in various areas such as optoelectronic devices, energy harvesting, and biomedical imaging. To enhance the stability, ZnS is often applied as a shell. MEIS-K120 analyzes the size and the composition of CdSe core and the thickness and the composition of the ZnS shell of CdSe/ZnS core/shell structure quantum dots. Figure 18 shows the MEIS spectra of ligand (perfluorooctanethiol) exchanged Lumidot (560 nm), Evidot (530 nm), and Evidot (590 nm). The quantity of ligand is analyzed by measuring the fluorine that consists of ligand as well.

Figure 18. The MEIS spectra and the analyzed structure of fluorinated (a) Lumidot (560 nm), (b) Evidot (530 nm), and Evidot (590 nm).
4-2. Conformal doping profile of FinFET (Under Development)

Fin-shaped field effect transistor (FinFET) is the 3D structure FET that is suggested to enhance the degree of integration of semiconductors. FinFET is named because its channel structure looks like a fin (figure 19(a)). The FinFET is built by fabricating Si to a series of fin on the substrate and implanting dopant at the wall of the fin. The doping profile of As is analyzed by MEIS with a 3D simulation. Figure 19(b) is the model structure of fin for MEIS simulation, and various doping levels of As are applied. As shown in figure 19(c), As peak at the MEIS spectrum is influenced systematically by the doping region and the concentration of As. For simulations of figure 19(c), 140 keV Ne⁺, 22.5° incident angle, and 135° scattering angle were used.

![Diagram of FinFET]

Figure 19. (a) Schematic diagram of FinFET. (b) The sample model for FinFET simulation. c) A MEIS spectrum simulation of FinFET as a function of concentration for side 1, side m, side 2 region. The concentration of As of the top and the bottom is kept as 10%.
Application 5: Pattern analysis

The MEIS spectrum of Cu mesh is measured for different positions with MEIS-K120. Cu mesh of 40 μm line width is attached to the manipulator with a carbon tape. Figure 20 (a), (b) is the image of MEIS-K120 equipped with optical microscope and the secondary electron (SE). The manipulator moves the blue and the red sites of a sample to the focused ion beam position. At the blue dot site (Cu line), the thick Cu spectrum is recorded, and at the red dot site (C tape), C substrate peak is recorded. MEIS-K120 is capable of monitoring the compositional depth profile of the contamination on the test pattern of the semiconductor comparably matching to 40 μm in size.

Figure 20. (a) 8x Optical microscope image of Cu mesh. (b) Secondary electron image of Cu mesh. (c) MEIS spectrum of blue and the red positions of Cu mesh on C tape.
Application 6: Strain profile (Under Development)

At the interface of Si and SiO$_2$, stress often occurs. It is caused by the volume increase during oxidation of Si, and this compressive stress is supposed to determine the reliability of gate oxide. The strain of the crystal sample is measured by monitoring the blocking dip of the sample using MEIS. If each blocking dip for a confined energy range of Si is measured, the information on the depth range of the Si is obtained. If the blocking dips are plotted according to the energy ranges of the Si peak in the MEIS spectrum, the depth in the sample is measured. If the strain varies according to the depth, the blocking dip shift varies according to the energy range. Figure 21 (a) shows the Si peak in the MEIS spectrum of 2 kinds of silicon oxide; thermal oxide and N$_2$O nitrided oxide at the 2.5° shifted double align condition. Figure 21 (b) shows the position changes of the blocking dips according the the energy range of Si peak. The blocking dips of the nitrided oxide do not show big changes throughout the energy range. On the other hand, the blocking dips of thermal oxide about 88-89 keV (SiO$_2$/Si interface) show shifts and the shift is larger at the higher energy (far from the Si substrate). In conclusion, the larger strain arises at the thermal oxide than the nitrided oxide.

![Figure 21](image)

Figure 21. (a) MEIS Si spectrum of a 7.7 nm thermal SiO$_2$ and N$_2$O nitrided SiO$_2$ with its blocking dip shift. (b) The shift of the Si blocking dip position as a function of depth around the [1 1 1] position.

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Application 7: Light element analysis by TOF-ERDA. (Under Development)

The depth profile of boron (B) of the silicon substrate is measured using the Time of flight- Elastic recoil detection analysis (TOF-ERDA) method. It is achieved by adding TOF in addition to ESA-MEIS. When the heavy incident ion such as Ar⁺ hits on the sample, elements lighter than an incident ion like B of the sample are recoiled at the same time that the Ar⁺ is scattered. In conventional MEIS, ESA cannot distinguish the B⁺ and Ar⁺ particles of same energy. In the TOF-MEIS, on the other hand, B⁺ and Ar⁺ vary in their velocities because of their different masses, resulting in a flight time difference. In this research, TOF follows the toroidal electrostatic analyzer (TEA) to resolve the particles by masses using different flight time after they are resolved by the energy. The sample is fabricated by 2 keV implantation of $1.5 \times 10^{16}$ B/cm². 100 keV Ar⁺ was used as a probe beam at the 75° incident angle, and the 50° scattering angle.

As shown in Figure 22(a), recoiled B⁺ is resolved from the scattered Ar⁺ by Si which has the same energy.

![Figure 22. (a) The flight time of B⁺ is different from that of scattered Ar⁺ of the same energy (TEA voltage 0.62 kV) (b) The total count of scattered and recoiled particles as a function of the TEA applied voltage.](image)