As with all of these lecture slides, I am indebted to Dr. Dieter Schroder from Arizona State University for his generous contributions and freely given resources. Most of (>80%) the figures/slides in this lecture came from Dieter. Some of these figures are copyrighted and can be found within the class text, *Semiconductor Device and Materials Characterization*. Every serious microelectronics student should have a copy of this book!
Ion Beam Characterization
Secondary Ion Mass Spectrometry
Rutherford Backscattering
Ion Beam Characterization

**Emission**
- Photon Spectroscopy
- Particle Induced X-Ray Emission
- Electron Emission

**Reflection**
- Sputtering
- Secondary Ion Mass Spectrometry
- Rutherford Backscattering

**Absorption**
- Ion Implantation

$E_i$
Secondary Ion Mass Spectrometry

- Ion Beam
- Screen
- Mass filter
- Microchannel Plate
- Mass Spectrometer
- Primary Ions
- Sample
- Secondary Ions
- CRT Image
- Spectrum
- Ion Counter
- Profile
Secondary Ion Mass Spectrometry

- Secondary ion mass spectrometry (SIMS) is the most common doping profile method.

  **Principle:** Atoms sputtered from the sample; mass of the ejected ions analyzed.
  - Ion mass $\Rightarrow$ element identification; ion intensity $\Rightarrow$ element density

- **Advantages:** Gives depth profiles. Can analyze all elements; most sensitive of all analytical techniques. Can measure several impurities simultaneously.

- **Limitations:** Destructive method. Subject to matrix effect: ion yields influenced by a change in surface composition. Need standards for concentration determination, independent depth measurement.

- **Sensitivity:** Depends on impurity. Highest sensitivity is boron in Si at $\sim 10^{14}$ cm$^{-3}$; all other elements less sensitive. Sensitivity limited by interference from ions of similar mass/charge.
**SIMS**

- Ion count $\Rightarrow$ density: use calibrated standard
- Time $\Rightarrow$ depth: measure depth of crater

![Graph showing Ion Counts and Density vs. Time and Depth](image-url)
Time-of-Flight SIMS (TOF-SIMS)

- Pulsed ion beam sputters the sample
- Ion time of flight is measured
- Measure transit time $\Rightarrow$ charge/mass ratio
- Low beam current $\Rightarrow$ low sputtering rate
- Suitable for organic surface contamination
- Sensitive for low metallic contamination ($\sim 10^8$ cm$^{-2}$)

$$t_i = \frac{L}{\sqrt{2V_{tof}}} \sqrt{\frac{m}{q}}$$

TOF-SIMS Example

- 70 Line Cu grid on Si wafer
  - Blue/green: SiO₂ features
  - Red/orange: tungsten features
  - Purple: chlorine and carbon contamination

www.llnl.gov/str/Hamza.html
TOF-SIMS Example

- Bond pad failure; covered with siloxane
- Siloxane mapped distinctly from elemental Si

Bonding pad with poor wire bond

www.materialinterface.com/surface5.html
The incoming ping pong ball loses the *most* energy when it is scattered from which of the four balls?

- Bowling Ball
- Baseball
- Tennis Ball
- Golf Ball
Rutherford Backscattering

- He ions with several MeV energy are scattered by the sample atoms
- The mass of the sample atom is determined from the energy of the scattered ions
Ion Scattering

- **Conservation of energy**

\[ E_0 = \frac{M_1 v_0^2}{2} = E_1 + E_2 = \frac{M_1 v_1^2}{2} + \frac{M_2 v_2^2}{2} \]

- **Conservation of momentum**

  _Parallel:_ \[ M_1 v_0 = M_1 v_1 \cos \theta + M_2 v_2 \cos \phi \]

  _Perpendicular:_ \[ 0 = M_1 v_1 \sin \theta - M_2 v_2 \sin \phi \]

- **Eliminating \( \phi \) and \( v_2 \)**

\[
\frac{v_1}{v_0} = \pm \sqrt{\frac{M_2^2 - M_1^2 \sin^2 \theta + M_1 \cos \theta}{M_1 + M_2}}
\]

- **For \( M_1 < M_2 \), use “+”**

\[
\frac{E_1}{E_0} = \left( \frac{\sqrt{M_2^2 - M_1^2 \sin^2 \theta + M_1 \cos \theta}}{M_1 + M_2} \right)^2
\]
Rutherford Backscattering

- He ions of 2-3 MeV are scattered; energy loss gives information
- Nondestructive
- Good for heavy elements on light substrate, e.g., silicides
- Sensitivity $\sim 10^{18} - 10^{19}$ cm$^{-3}$
- $K$: kinematic factor
- $R = M_1/M_2$

\[ K = \frac{E_1}{E_0} = \frac{\sqrt{1-(R \sin(\theta))^2} + R \cos(\theta)}{(1+R)^2} \]
Rutherford Backscattering

- RBS works best for heavy elements on light substrates.

![Diagram showing Rutherford scattering with He, 1-3 MeV.](image)

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

- 100 nm TiN on Si

- Si Substrate

- Ti
Rutherford Backscattering

- RBS works best for heavy elements on light substrates

\[
Yield = \sigma \Omega QNt
\]

\[
\sigma = \frac{q^2 Z_1 Z_2}{4E} \frac{4}{\sin^4 \theta} \left( \frac{1 - (R \sin \theta)^2 + \cos \theta}{\sqrt{1 - (R \sin \theta)^2}} \right)^2
\]

- \(\sigma\): scattering cross section
- \(\Omega\): solid detector angle
- \(Q\): no. of incident ions
- \(N\): target atom density
- \(t\): thickness
Rutherford Backscattering

Energy Channel

Yield

Si C N O Si Ti

3.7 MeV He

100 600

Pa-n Ag

ECE 4813 Dr. Alan Doolittle
Channeling

- He ions are scattered more when they are not channeled.

*Scient. Am.* 218, 90 (March 1968)
Thickness Measurements

- Thickness determined by measuring the various energies

\[ E_3 = K_1 E_0 \; ; \; E_2 = K_1 (E_0 - \Delta E_{in}) - \Delta E_{out} \]

\[ \Delta E = E_3 - E_2 = K_1 \Delta E_{in} + \Delta E_{out} = [S_0]d \]

\([S_0]\): backscattering energy loss factor (eV/Å)

\[ E_1 = K_2 (E_0 - \Delta E_{in}) - \Delta E_{out} \]
Silicide Formation

- RBS is ideal for measuring the formation of silicides

M.A. Nicolet et al. Science, 177, 841 (1972)
RBS Examples

Review Questions

- What is the main application for SIMS?
- What is the principle for RBS?
- What is TOF-SIMS?
- What is channeling?
- How are the SIMS vertical and horizontal data converted?