GIXUVR - Grazing Incidence Extreme Ultraviolet Reflectometry: an All-Optical Technique for Metrology of Ultra-Thin Layers

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In order to miniaturize today’s metal oxide semiconductor field effect transistors even further, channel lengths and gate dielectric thicknesses need to decrease. Traditionally deployed SiO₂ dielectrics face serious difficulties due to rising leakage currents and need to be replaced by alternative (high-k) materials with a larger dielectric permittivity and equivalent oxide thickness in the future. A current focus of the industry is centered on thin films of HfO₂ as a promising candidate for further scaling of such devices. Characterization of these layered systems is mandatory to measure and control the interface between substrate and high-k material as it can severely influence its electric properties. Here we propose a novel metrology technique, namely Grazing Incidence Extreme Ultraviolet Reflectometry (GIXUVR), utilizing short wavelength radiation from off-synchrotron sources for the analysis of such thin-film structures. Benefits of the method are the rapid measuring time (on the order of milliseconds to seconds) as well as high thickness, density and material sensitivity due to the very efficient interaction of extreme ultraviolet light (XUV, 1-50 nm, or EUV, at about 13.5 nm) with matter.

**Extreme Ultraviolet Radiation**

- refractive index close to unity
- all materials highly absorptive
- low penetration depths
- HV conditions necessary
- surfaces highly reflective for XUV under grazing incidence

**Application: Analysis of Ultra-Thin Layers in High-k Gate Dielectric Stacks**

**Proof-of-Principle Investigations at PTB, BESSY II**

- GdScO₃ gate stack with differing „parasitic“ oxide thickness

**Characterization of Ultra-Thin Oxides on Wafers**

- laboratory GIXUVR investigation of natural / thermally grown oxides

**Database build-up for relevant materials**

- refractive index (n = 1 – 6 + i8) determination in XUV from multi-angle reflectivity measurements

**Cross-characterization of a HfO₂ gate dielectric stack**

- Investigation of a typical HfO₂ / SiO₂ / Al interface (CNSE Albany, USA)

**Benchmarking of techniques**

<table>
<thead>
<tr>
<th>Technique</th>
<th>MEIS</th>
<th>ARXPS</th>
<th>GIXUVR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>km</td>
<td>photon</td>
<td>photon</td>
</tr>
<tr>
<td>Beam size</td>
<td>mm</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>Flux</td>
<td>10⁸/cm²/sterad</td>
<td>0.5 pm</td>
<td></td>
</tr>
<tr>
<td>Measuring time</td>
<td>h/m/s</td>
<td>s</td>
<td>s</td>
</tr>
<tr>
<td>Required vacuum</td>
<td>10⁻⁵ mbar</td>
<td>10⁻⁴ mbar</td>
<td>10⁻⁴ mbar</td>
</tr>
</tbody>
</table>

1. High sensitivity, fast measurements, high accuracy
2. Depth of analysis if significant layers are buried even deeper, model dependent layer parameters
3. High surface sensitivity, thickness / roughness / material dependence
4. Absorption edges of materials accessible (e.g., Si @ 12.4 nm, Al @ 17 nm)

**Extensive list of references**

- GdScO₃: majority of N (≈75%) incorporated into HfO₂ layer, likely presence of Hf₄N₄
- ARXPS: nitrogen presence confirmed, diffusion near to the substrate, interdiffusion <0.5 nm
- GIXUVR: agreement with ARXPS results, deviations from bulk densities required to generate best fit