Metrology in Nanotechnology

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Introduction

• We are now in a very exciting period of time when many new and disruptive technologies emerge across a wide range of industries.

• The new products with emerging technologies are generally smaller, lighter, stronger, more reliable and cheaper, which require better process control, and more upstream in the manufacturing processes.

• This trend brings not only good opportunities, but also new challenges to integrate various metrology tools into the advanced manufacturing processes.

• In this talk, I will review and compare several metrology tools that Bruker provides, and their applications in nanotechnology. I will also discuss about some of the challenges in integrating the tools into the manufacturing process.
This presentation includes data and materials from various technical, application and sales presentations, which were contributed by many colleagues worldwide at Bruker.

Some materials are from Bruker’s customers, who have gracefully shared their experiences with our equipment and agreed to help us demonstrate our equipment capabilities.

The presenter would like to sincerely thank all people who have contributed to the materials included in this presentation.
Outline

• Technology review
• Examples of imaging metrology applications
  • Wafer level package
  • Flexible films
  • MEMS
• Summary
Bruker Nano Surfaces Division
Leading Metrology Technologies

- AFM, Scanning Probe Microscopy
- Optical Profilometry
- Stylus Profilometry
Atomic Force Microscopes

- High resolution 3D surface imaging by rastering a nm size probe across surface
- Can also measure electrical, magnetic, mechanical, thermal & some chemical properties
- Primary application areas:
  - (Nano)materials Research
  - Biology/Life science Research
  - Semiconductor/Data Storage
Atomic Force Microscopy Application-Optimized Models

Entry-level Research

24/7 industrial

Life Science

High-End Research & High Throughput
Carbon nanotube pillar array. Image size 1 micron. PeakForce TUNA current image reveals strong conductivity variation, possibly due to differences in nanotube types or capping.
Material Property Maps

Get quantitative and high resolution on modulus, adhesion, and conductivity.
High speed AFM studies of PHBV crystallization show lamella spurting forward substantially faster than the macroscopic growth rate, then slowing or stopping. Growth is then controlled by the rate of lamella nucleation on dormant lamella, rather than by the growth rate of individual lamella (see Hobbs, Bruker).

2.2 micron images, 100Hz, 256 x 256 pixels. Sample Courtesy: Dr. Jamie Hobbs University of Sheffield
Dektak Stylus Profilers

- Measures surface profile by moving stylus across sample.
- Low cost, easy to use.
- Primary applications:
  - Roughness
  - Step Height

50nm radius, FIB-etched diamond tips
Stylus Profiler Capabilities

- **Large Part Ranges**
  - Wafers >200 mm
  - Parts up to 100mm tall
  - Sample thickness up to 50mm
  - Vertical scan range to 1mm
- **Low stylus force**
  - Down to 0.03mg
- **Step height repeatability**
  - 5 Å
- **Full XY automation for 3D Mapping**
- **Reference optical flat for best results in film stress measurement**
Stylus Profiler Capability
Illustrations

Full 4” wafer profile

Same head covers step from **1nm to 1mm** with force range from **0.03mg to 15mg.**
Stylus Profiler
3D Mapping Examples

Optics

MEMS

Ink Jet Nozzles

Polyester Weave
Optical Interferometry Profilers

- 3D microscope for surface profiling based on White Light Interferometry (WLI)
- Non-contact, non-destructive
- Fast, accurate, and repeatable
- Sub-nanometer vertical resolution
- Image large areas at once

Key application areas:
- Automotive/Aerospace
- Data Storage
- Solar
- MEMS
- Semiconductor
- LED, Optics
- Medical
- Precision Machining/Tribology
3D Optical Profilers
Table top to high end automation

ContourGT-I
Table top automated
ContourGT-K
manual

ContourGT-X
Advanced automation
with wafer loader capability

Dual 300mm FOUP
ContourGT-X ARM
Configuration

SP – flat panel, 
large substrate and PCB
Interference fridges are similar to contour map lines

- On a contour map each line represents a fixed elevation.
- Typically the spacing is 100 feet
- Set by the mapmaker

- On an interferogram each line also represents a fixed height
- Spacing is 1/2 the wavelength of the light (typically 300nm in current instrument)
- Set by optics
### 3D Optical Interferometry

#### White Light Interferometry – WLI
- **VSI** – white light illumination
- Vertically scan through focus, looks for highest fringe contrast
- Vertical resolution $\sim 3$ nm
- Rough surfaces, steep steps
  - Height range: $< 10$mm
  - Slope: $< 60$deg
- Speed: 5-80um/sec

#### Phase Shifting Interferometry – PSI
- **PSI** – monochromatic illumination
- Calculates the phase of the fringes
- Vertical resolution $< 0.1$ nm
- Optically smooth surfaces
  - Height range: $< 140$nm
  - Ra: $< 30$nm
- Speed: $\sim 1$ sec
PSI – High Vertical Resolution

- 0.02nm Ra, 0.7nm PV
- SiC mirror with 0.14nm Ra
- 0.2nm deep scratches are visible
VSI – Versatile Applications

Metals

Life Sciences

MEMS
(MicroElectroMechanical Systems)

Semiconductors

Optics

Materials
VSI – More Applications

Human Skin

Hard disk suspension arm

Electronic circuit

Cotton cloth, 1mm x 1mm

Microfluidic

Grasshopper Eye 230um x 300um.
Stitching Enables Large Area Metrology

- Stitch up to 2000 fields together for large area imaging with high spatial resolution,
- Fields of view up to many square cm
Transparent Film Thickness Measurement

- Interferometer creates two sets of fridges at:
  - air/film interface
  - film/substrate interface.

- Position of the peaks, corrected for the film material, gives film thickness

- 400nm to 200 µm films can be characterized.

- Repeatability: 2-6nm

- Film Thickness and Surfaces Simultaneously Characterized

Unlike Stylus, Optical Techniques Do Not Require Steps
Manufacturers need to understand how devices perform in their final state, often through packaging.

Environmental testing is also required, typically in test chambers under varying temperature, pressure, etc.

Challenge: when measuring through transmissive media the optical path length differs between the two arms of interferometer:

- Decreased fringe contrast
- Difficult to make accurate measurements

At low magnification compensation is possible by introducing a slide of similar material and thickness in the reference arm.
Custom Objective Enable Measurement Through Glass

- Micro-mirror array imaged through the window (170um) of an environmental chamber

*Courtesy Sandia National Laboratories.*
Wafer Level Packaging
Process Monitoring

- Need to verify proper etch and plate dimensions for Cu traces, pillars in process across wafers

- Fast feedback on process is not easily achieved via SEM (current workhorse)

- Fast, non-contact solution available from Bruker for...

- Automated CD inspection of Cu trace widths, heights

- UBM diameters, Cu pillar heights

- Cu Roughness

- Film thicknesses during process
Copper Pillar / Solder Bumps Height / Width and PR (photo resist) Thickness

One measurement, multiple analyses done simultaneously
Film Measurement capability separates two signals and measures the thickness without a step height.

Both Copper and Film thickness in a single measurement.
CD/Width, Height and Roughness of UBM in a Single Measurement
Lead Frame Roughness
Before and After Process

Ra: 204nm

Ra: 114nm
Defects and CD Variations of Any Layer Can Decrease Performance, Lower Yields, and Increase End of Line Scrap and Product Cost
Polymer substrates
Roughness & waviness measurements

- Fine features and large waviness affects:
  - Adhesion of deposited film
  - Longevity of deposited film

- Requirements:
  - Fast
  - Large field of view
  - Vertical resolution below 1nm
Defect Detection and Analysis on Flexible Film

Courtesy of Karl Rakos, DuPont Teijin Films
MicroElectroMechanical Systems (MEMS)

- Manufactured using techniques similar to those of semiconductors
- Feature sizes typically 1-100µm
- Applications: automotive sensors, optical network switches, displays, projectors, medical devices, etc.
Optical Profiling Advantages for MEMS manufacture

- 3D visualization of part performance
- Non-contact—will not deflect or deform structures
- High vertical resolution captures optical-grade surface roughness
- Vertical range for large steps and thicknesses
- Lateral resolution and feature-tracking software for critical dimension analysis
- Static and dynamic measurement provide comprehensive analysis in a cost-effective, single platform
- Rapidly image entire device, and analyze multiple features, at high vertical resolution
Roughness Measurement

- Characterize surfaces from super-smooth to very rough
- 3D parameters provide directionality, periodicity, peaks vs troughs, etc—far more than just average roughness
- Control film deposition processes
Step Height Measurement

- Measure Step heights from nanometers to 8mm
- Determine thickness of films and resists for process control
- Monitor deposition and etch processes
Static measurement quantifies individual features and films.

Dynamic measurement lets you visualize and quantify true device functionality during actuation.

Static measurement of ESD-damaged resonator (Courtesy CNRI MEMS Exchange)

Dynamic measurement of resonator (Courtesy Sandia National Labs)
## Comparison of Metrology Techniques

<table>
<thead>
<tr>
<th></th>
<th>Optical Interferometry</th>
<th>Stylus</th>
<th>AFM</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3D Measurement</strong></td>
<td>Quantitative</td>
<td>Quantitative</td>
<td>Quantitative</td>
<td>Qualitative</td>
</tr>
<tr>
<td><strong>Sample Interaction</strong></td>
<td>Non-contact, Non-destructive</td>
<td>Contact</td>
<td>Intermittent Contact, Non-destructive</td>
<td>Non-contact, Electron bombardment</td>
</tr>
<tr>
<td><strong>Acquisition Speed</strong></td>
<td>&lt; 5 secs/area</td>
<td>5 secs/line</td>
<td>0.5 sec/line</td>
<td>20 – 320 seconds/image</td>
</tr>
<tr>
<td><strong>Vertical Measurement Range</strong></td>
<td>Up to 10 mm</td>
<td>1mm</td>
<td>20 um</td>
<td>~10um depth of field</td>
</tr>
<tr>
<td><strong>Vertical Resolution</strong></td>
<td>&lt;1 A</td>
<td>&lt;5A</td>
<td>&lt;1 A</td>
<td>2nm – 10nm</td>
</tr>
<tr>
<td><strong>Lateral Resolution</strong></td>
<td>0.2 um</td>
<td>&gt;1um</td>
<td>&lt;5nm</td>
<td>2nm – 10nm</td>
</tr>
</tbody>
</table>

| **Price**               | $80K-$200K              | <$50K | >$100K                   | $80K - $500K                         |
Metrology Analysis Ranges

![Graph showing metrology analysis ranges for different types of microscopes.](Image)

- **Optical Profiler**
- **Stylus Profiler**
- **Atomic Force Microscope**
- **Scanning Electron Microscope**

**Feature Height**
- nm
- μm
- mm

**Lateral Feature Size**
- nm
- μm
- mm

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Optical And Stylus Systems are Complementary

- **Stylus**
  - Sub-nm vertical resolution
  - 1mm vertical range
  - Rapid single traces
  - **Insensitive to material effects**
  - Accurate and repeatable
  - Variable lateral resolution
  - Slower for 3D
  - Requires contact with surface

- **Optical**
  - Sub-nm vertical resolution
  - 10mm vertical range
  - Rapid, full-field 3D measurements
  - Sensitive to material effects
  - Accurate and repeatable
  - Variable lateral resolution
  - Constant vertical resolution
  - Handles transparent materials
Challenges

• Manufacturing environment may introduce noise in the measurement
  • Mechanical vibration
  • Acoustic noise
  • Temperature fluctuation
  • Contamination
• Equipment self heating may cause thermal drift of the system
• Complex sample geometry and material combination may cause artifacts in measurements
Summary

• Metrology tools will play an important role in the emerging technology advancement.

• Optical interferometers are widely used as process motoring tools because they can quickly cover a large area, and are very versatile. They are best to be used for critical dimension, film thickness, and roughness measurements. They can also be used for defect detection and analysis.

• Stylus profilers are also very useful tools because they are low cost and easy to use. They are best to be used as monitoring tools for step height and roughness measurements.

• AFM is the ultimate metrology tool for resolution in the sub nanometers. It can also measure material properties in the nanometer scale. High speed AFM opens opportunities for understanding of new technologies.
• Let’s have some fun now ...
MEMS Gear
- Miniaturized machines
- Pressure sensors
- Cantilevers...
50nm Polystyrene Beads
DNA Origami
nm-scale Map of France

Antidot Pattern on GaAs

Created with AFM ‘Nanolithography’

Courtesy: F. Perez, CNM Barcelona

Courtesy: A. Dorn, ETH Zurich