Ion-Beam Sputtering in Industrial Production

Dr. Volker Scheuer
Part 1

- Basics of Ion Beam Sputtering (IBS) Technology
- Breakthroughs by IBS coatings

Part 2

- IBS Technology at NANEOP
- Examples of IBS Coatings by NANEOP
  - Broad Band Gain Flattening
  - High Power Beam Combining
  - High negative Dispersion
  - High Damage Coatings
E > displacement energy about 20 – 25 eV

Process Parameters:
- Ion Energy
- Ion Mass
- Sputter Angle
- Reactive Gas Pressure
- Substrate Position
- Electron current
- ...
Energy distribution of sputtered particles

Most particles = 5 eV but many particles have higher energy

Computer Simulation Program SRIM

*Stopping and Range of Ions in Matter*

by

Jochen P. Biersack and James F. Ziegler

Primary Energy: 1200 eV
Sputter Angle: 55 °
Target: Titanium Oxide
Maximum: ~ 5 eV
Energy transport of the particles

50% Energy Input by Particles with Energy > 100 eV

Energy Contend in % for
Low Energy Particles  $E_L$
High Energy Particles  $E_H$
sputtering from Ti Target

<table>
<thead>
<tr>
<th>Gas</th>
<th>$E_L$</th>
<th>$E_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>40.1</td>
<td>59.9</td>
</tr>
<tr>
<td>Ar</td>
<td>48.8</td>
<td>51.2</td>
</tr>
<tr>
<td>Xe</td>
<td>49.5</td>
<td>50.5</td>
</tr>
</tbody>
</table>
Sputter angle of different particle groups

High Energy and Back Scattered Particles are sputtered to larger angles

Particle Groups:
- $E_L$ : Low Energy Particles Ti
- $E_H$ : High Energy Particles Ti
- $E_B$ : Back Scattered Primary Particles of Argon
Process of Ion Beam Sputtering

Process Parameters:
- Ion Energy
- Ion Mass
- Sputter Angle
- Reactive Gas Pressure
- Substrate Position
- Electron current
- ...

www.naneo.com
NTB Buchs 11.6.2015
Summary: Basics of IBS

- Energy necessary for high quality coating
  - \( > \) displacement energy: 20-25 eV
  - \(< \) defect creation
  - Values differs for coating materials

- IBS Energy input to coating is controlled by
  - Energy of primary ions
  - Mass of the primary ions
  - Position of the substrate area
  - Assist beam

- Standard IBS Materials: Oxides from Si, Ta, Ti, Nb, Hf, Zr
Breakthroughs by IBS coating technology - 1 (since 1980)

MIRRORS FOR RING LASER GYROSCOPES (RLGS) FOR NAVIGATION since > 1980

Honeywell GG1320AN digital ring laser gyro
Height: 45 mm, diameter: 88 mm, weight: 450 g
Random Walk < 0.04 degree/hour

Sagnac effect
- 2 counter propagating waves
- platform rotation > phase shift
- shift detected interferometric
- 3 mirrors with very low losses
- scatter losses very important
Breakthroughs by IBS coating technology – 1

Super polished Substrates: Roughness < 1 Å are necessary

<table>
<thead>
<tr>
<th>Mirror</th>
<th>AOI [°]</th>
<th>T (ppm)</th>
<th># of layers</th>
<th>Reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>90 ± 10</td>
<td>30</td>
<td>&gt;99.9890</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>90 ± 10</td>
<td>30</td>
<td>&gt;99.9890</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>&lt; 20</td>
<td>34</td>
<td>&gt;99.9960</td>
</tr>
</tbody>
</table>

Recommended Losses: Scattering (TIS) < 10 ppm
Absorption < 10 ppm

Loss values of a 45° mirror given by Vecco

<table>
<thead>
<tr>
<th>Materials</th>
<th>Total Loss</th>
<th>Transmission</th>
<th>Scatter</th>
<th>Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂·Ta₂O₅</td>
<td>7.8</td>
<td>3.9</td>
<td>0.8</td>
<td>3.1</td>
</tr>
<tr>
<td>SiO₂·Ta₂O₅</td>
<td>8.5</td>
<td>3.9</td>
<td>0.9</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Values given in parts per million (ppm) @ 633 nm (He Ne Laser)

Measured by PSI: Phase Shift Interferometer
Breakthroughs by IBS coating technology – 2  (since 1995)

DWDM Filters: Wavelength Multiplexing for Fiber-Communication

Divided into 300 Channels

1490.76 S C 1610.06 nm
201.10 197.10 191.10 186.20 THz

1551.32 1551.72 1552.12
193.25 193.20 193.15

0.4 nm

System design:  N = 189
D = 50 000 nm

System Stability: 0.1 nm  humidity change

System total view

Similar Systems: Raman filters
Summary Part 1: High Quality of IBS coatings

- Very low scatter losses
- Very low absorption losses
- Very dense and stable

Best applicable for Laser Coatings
Mission of **NANEO**

We provide for our customers

- Highest coating quality by IBS Coating Technology
- Highest coating precision by in house Broad Band Optical Monitoring
1. IBS Coating Machine
2. IBS Coating Machine
IBS in industrial production

- Very stable process
  - coatings rates < 0.5%
  - material dispersions < 0.1%

- Coating rates 2 – 3 A/sec

- Fully computer controlled operation in 24 hour modus

- Routinely Maintenance
  - source grids 200-300 h
  - neutralizers > 1000 h
  - shields 50 - 500 h
IBS Coating Machine with Optical Monitoring System

Light Source
Beam Splitter
Mirror
Assist Source
Sputter Source
Targets
Masks
Substrates
Detector
450-1650 nm
Cryo Pump

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Resolution Demonstration of Optical Monitoring

Measurement of 2 very thin coating steps within one layer

Resolution below 1 Angstrom  \( \iff \Delta th < 0.001 \)
Output Coupler for Gain Flattening

- Mirror Output is matched with laser gain for uniform output power
- Low tolerances over broad bandwidth

Design Date and Tolerances
System data: no layers: 37
  total thickness: 3900 nm

Statistical Error Calculation
\( \Delta n = 0.003, \Delta t h = 0.003, N = 200 \)
Output Coupler with Gain Flattening

Production result and statistical error sensitivity

- Measurement by Transmission Spectrometer
- Statistical Error Calculation
  \[ \Delta n = 0.001, \Delta \text{th} = 0.001, N = 200 \]

Production result within statistical error region \( \text{Exp} \pm D \)

**Statistical Thickness and Dispersion Error <= 0.1%**
High Power Beam Combiner

Wavelength Combining of Laser Beams

\[ \lambda_i = \lambda_i(s-pol) + \lambda_i(p-pol) \]

\[ P(\lambda_i) \sim 5kW \]

System Design Data:
- no layers: 87
- total thickness: 16650 nm
High Power Beam Combiner

Production result

- **Design S-Pol**
- **Design P-Pol**
- **Measurement S-Pol**
- **Measurement P-Pol**

![Graph showing transmission vs. wavelength with marked design and measurement data points]
High Power Beam Combiner

Production Result Transmission Range

Measurement by Transmission Spectrometer

Statistical Error Calculation
\[ \Delta n = 0.0008, \Delta th = 0.0008, N = 200 \]

Statistical Thickness and Dispersion Error << 0.08%
High Dispersion Mirror HDM @ 1030 nm with -3000 fs²

Compensation of positive dispersion on beam path

System data: no layers: 67 - total thickness: 9263 nm
**Production Precision**

**Graph 1:**
- Design: Blue line
- Measurement: Red line

**Measurement by white light interferometer**

**Statistical Error Calculation**

\[ \Delta n = 0.0005, \Delta th = 0.0005, N = 200 \]

**Production result within statistical error region Exp +/-D**

**Production error in layer thickness < 0.05 % \(\leq\) \(\Delta th < 1\) Angstrom**
## LIDT of Naneo Coatings

<table>
<thead>
<tr>
<th>Coating System</th>
<th>LIDT Specification</th>
<th>LIDT Value [J/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR 1064 nm, R&gt;99.98</td>
<td>@ 1064 nm 20 ns 1 on 1, f_{rep}=20 Hz</td>
<td>90 / 140</td>
</tr>
<tr>
<td>Mat: Ta₂O₅, SiO₂ Substrate super polished</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR 786 nm, R&gt;99.9</td>
<td>@ 786 nm 180 fs f_{rep}=1kHz n on one, 10⁵</td>
<td>0.65</td>
</tr>
<tr>
<td>Mat: Ta₂O₅, SiO₂ Standard QWOT Field Optimized</td>
<td></td>
<td>1.20</td>
</tr>
<tr>
<td>AR 786 nm, R&lt;0.01</td>
<td>@ 786 nm 180 fs f_{rep}=1kHz n on one, 10⁵</td>
<td>1.20</td>
</tr>
<tr>
<td>Mat: Ta₂O₅, SiO₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dichroic 390 nm, R 786 nm, R</td>
<td>@ 393 nm 180 fs f_{rep}=1kHz n on one, 10⁵</td>
<td>0.39</td>
</tr>
<tr>
<td>Mat: Al₂O₃, , SiO₂</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Summary

• IBS is a very well controllable and stable production process

• Very high quality coatings can be produced in industrial scale

• Systems with very high spectral or phase broad band specifications can be produced routinely

• Coatings have very low scatter and absorption losses

• Coatings achieve high damage thresholds
Thank you for your attention