A New X-Ray CD-Metrology for Nanostructure BPM Patterns

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Worldwide Best X-ray Partner

Leading with Innovation

Diskcon-US 2010 Hyatt Regency Santa Clara

HQ, Fab:

Subsidiary:

Distributor:

USAsales:

Beijing
Shanghai
RC
SSI
RAC
RIT
REHQ
Berlin
Tokyo
Yamanashi
Osaka
NSI
RITE

Rigaku Who?

Worldwide Largest X-ray Scientific Instrument Company

SmartLab
XtaLABmini
Supermini

Rigaku

3650
TXRFV300
MFM65

Worldwide Largest X-ray Scientific Instrument Company

TXRFV300
MFM65
Agenda

1. Market Outlook and Background
2. Why X-ray diffraction method for inspection?
3. Grazing Incidence X-ray diffraction
4. Example of Grating measurement
5. Example of DTR measurement
6. Simulation of BPM measurement
7. Summery
Market Outlook:
HDD shipment is projected a healthy increase by the PC & external storage demands

- Mobile applications will overtake Desktop
- Cloud and External storage in the home will coexist

Source: IDC 2010, 2009
Data Flash Density Trend

![Data Flash Density Trend Diagram](image)

- **Density (Gb)**
  - 1000
  - 100
  - 10
  - 1

- **Year**
  - 2008
  - 2009
  - 2010
  - 2011
  - 2012
  - 2013
  - 2014

- **Data Flash Density Trend**
  - 16.384 (40nm)
  - 32.768 (32nm)
  - 65.536 (27nm)
  - 131.072 (22nm)

- **Source:** Forward Insights

Next NAND Flash Technology

- **Multi-Chip TSV**
  - Thickness: 20µm

- **Die Stacked:** 32 (Samsung)

- **8 layers Prototype NAND Flash Memory Stack**

**Diskcon-US 2010 Hyatt Regency Santa Clara**
Technology and Historical Areal Density Trend

- MR Head
  - Thin Film Media
  - PRML Channel etc.
- AFC LMR TMR Head
- 25%CGR
- 60%CGR
- Advanced PMR
  - DTR
  - BPR
  - TAR
- PMR TFC etc.
- CPP GMR
- 20-40%CGR
- GMR Head
  - MEPRML Channel etc.
- 60%CGR
- 90%CGR

Areal Density (Gb/in²)

Year (Product Available: Mobile)

Source: Diskcon-Japan 2010 (HGST)
New Technology for Higher Density Recording

Magnetic Head
- Thermally Assisted Recording (TAR)
- Microwave Assisted Magnetic Recording (MAMR)
- Shingled Magnetic Recording (SMR)

Media
- Discrete Track Media (DTM)
- Bit Patterned Media (BPM)

Combination of TAR and BPM is expected to the high density recording of >10Tb/in²

Source: Diskcon-Japan 2010 (Hitachi)
Low cost patterned media production by duplication

DTM & BPM production

- Nano structures of the Master and Template should be observed precisely, because finally 100,000,000 of products are duplicated from the Master.
- The duplication process from the template to the products is assumed to be checked at least once by the inspection tool.
The Metrology for the DTM & BPM inspection

Why X-ray diffraction method for inspection?

- The possibility to measure < 10nm without standard
- Non-destructive/non-contact precise inspection
- Resist pattern measurement is possible without damage

<table>
<thead>
<tr>
<th>Flash 1/2 pitch (nm)</th>
<th>2010</th>
<th>2013</th>
<th>2016</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRAM ½ Pitch (nm)</td>
<td>45</td>
<td>32</td>
<td>22</td>
<td>16</td>
</tr>
<tr>
<td>MPU Printed Gate Length (nm)</td>
<td>41</td>
<td>28</td>
<td>20</td>
<td>14.0</td>
</tr>
<tr>
<td>MPU Physical Gate Length (nm)</td>
<td>27</td>
<td>20</td>
<td>15.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Wafer Overlay Control (nm) - 20% DRAM</td>
<td>9.0</td>
<td>6.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Wafer Overlay Control Double Patterning (nm)</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Lithography Metrology</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical CD Control (nm)</td>
<td>2.8</td>
<td>2.1</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Wafer CD metrology tool uncertainty (3σ, nm) at P/T = 0.2</td>
<td>0.55</td>
<td>0.42</td>
<td>0.31</td>
<td>0.25</td>
</tr>
<tr>
<td>Etched Gate Line Width Roughness (nm) &lt;8% of CD</td>
<td>2.1</td>
<td>1.6</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Printed CD Control (nm)</td>
<td>3.3</td>
<td>2.3</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Wafer CD metrology tool uncertainty (3σ, nm) at P/T = 0.2</td>
<td>0.7</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>
GI configuration of X-ray Diffraction Measurement

Rotation of the sample is necessary for satisfying diffraction condition: \( Q \cdot a = 2\pi h \)

X-rays irradiate sample surface with grazing incidence angle. Diffracted x-rays are detected by two-dimensional detector.
X-ray Diffraction Intensity Evaluation-1

Periodic structure on the surface

\[ a = \overline{X}_{j+1} - \overline{X}_j \]

Incident x-ray

\[ \alpha \]

Diffraction intensity

\[ I(\mathbf{Q}) = r_e^2 P^2 \sum_j e^{-i\mathbf{Q} \cdot \mathbf{r}_j} F_j(\mathbf{Q}) \]

\[ = (r_e P)^2 \left\{ \sum_j |F_j(\mathbf{Q})|^2 + \sum_{j \neq k} F_j(\mathbf{Q}) F_k^*(\mathbf{Q}) e^{-i\mathbf{Q} \cdot (\overline{u} - \overline{u})} e^{-i\mathbf{Q} \cdot (\overline{X}_j - \overline{X}_k)} \right\} \]

\[ = (r_e P)^2 N \left\{ |F_j(\mathbf{Q})|^2 + \sum_{|\mathbf{Q}| \geq 1} \langle F_j(\mathbf{Q}) F_{k+j}^*(\mathbf{Q}) \rangle e^{-i\mathbf{Q} \cdot (\overline{X}_j - \overline{X}_{k+j})} \right\} \]

For the large number of \( N \), only the term, \( \mathbf{Q} \cdot (\overline{X}_{j+1} - \overline{X}_j) = 2\pi h \), can be remain.

Diffraction condition

\[ \mathbf{Q} \cdot \mathbf{a} = 2\pi h \]

\( h \): Integer (index of diffraction)

\( r_e = 2.818 \times 10^{-15} \text{ m} \): classical radius of electron

\( P \): polarization factor
X-ray Diffraction Intensity Evaluation-2

Incident wave: \( E_1^i(\alpha) = T_1(\alpha)e^{-ik_0Z_1n_1(\alpha)} + T_1(\alpha)R_1(\alpha)e^{ik_0Z_1n_1(\alpha)} \)

Diffracted wave: \( E_1^d(\beta) = T_1^*(\beta)e^{ik_0Z_1n_1^*(\beta)} + T_1^*(\beta)R_1^*(\beta)e^{-ik_0Z_1n_1^*(\beta)} \)

Transmission and reflection coefficients:

\[ R_1(\alpha) = \frac{\eta(\alpha) - \eta_2(\alpha)}{\eta(\alpha) + \eta_2(\alpha)}, \quad \gamma(\alpha) = \frac{\sin\alpha - \eta(\alpha)}{\sin\alpha + \eta(\alpha)}, \quad \eta_1(\alpha) = \sqrt{n_1^2 - \cos^2\alpha} \]

\[ T_1(\alpha) = \frac{\tau_0}{\eta_1(\alpha) + \eta_2(\alpha)}, \quad \eta_1(\alpha) = e^{ik_0d_1}, \quad \tau_0 = \frac{2\sin\alpha}{\sin\alpha + \eta_1(\alpha)} \]
Parameters determinable by X-ray Diffraction Measurement

\[
F(\alpha, \beta, Q_{||}) = T_1(\beta)T_1(\alpha)
\]

Cross-sectional profile of the grating

Form factor of the unit with surface reflection correction

\[
\begin{align*}
&\int \rho_1 \left( e^{-\frac{i k_0 (\eta_1(\alpha) + \eta_1(\beta)) z(x,y)} - 1 e^{-i(Q_x \cdot x + Q_y \cdot y)} dX dY} \\
&+ R_1(\alpha) \int \rho_1 \left( e^{-\frac{i k_0 (\eta_1(\alpha) + \eta_1(\beta)) z(x,y)} - 1 e^{-i(Q_x \cdot x + Q_y \cdot y)} dX dY} \\
&+ R_1(\beta) \int \rho_1 \left( e^{-\frac{i k_0 (\eta_1(\alpha) - \eta_1(\beta)) z(x,y)} - 1 e^{-i(Q_x \cdot x + Q_y \cdot y)} dX dY} \\
&+ R_1(\alpha) R_1(\beta) \int \rho_1 \left( e^{-\frac{i k_0 (\eta_1(\alpha) - \eta_1(\beta)) z(x,y)} - 1 e^{-i(Q_x \cdot x + Q_y \cdot y)} dX dY} \right) \right)
\end{align*}
\]
Simulation of X-ray Diffraction Intensity Distributions-1
Simulation of X-ray Diffraction Intensity Distributions-2

- **Bottom rounding**
  - Exit angle $\beta / 10^2$ deg vs. Diffraction index $h$

- **Top rounding**
  - Exit angle $\beta / 10^2$ deg vs. Diffraction index $h$
Actual Tool for X-ray Profile Metrology-1
**Application**
Line and Space profile measurement of resist, Si or 6025 Quartz

**Performance**
- Less than 64nm Half Pitch
- Less than 150nm height
- Measurement area 2-3mm(X) by 1mm(Y)
- Precision <1nm (3 sigma)
- Measuring time 100 sec/point
Measurement of Standard SiO$_2$ Grating for CD-SEM

Each diffraction peak elongated to vertical direction (so called Bragg rod) and shows clear fringes reflected to cross-sectional structure of the grating.
Least Square Fitting of the Grating Profile Parameters-1

Structural parameters are optimized by minimizing residuals between observed and calculated diffraction patterns using least square analysis.
Least Square Fitting of the Grating Profile Parameters-2
### Least Square Fitting of the Grating Profile Parameters

#### Observed structural parameters

<table>
<thead>
<tr>
<th></th>
<th>Pitch (nm)</th>
<th>Line width (nm)</th>
<th>Height (nm)</th>
<th>SWA (deg)</th>
<th>Top radius (nm)</th>
<th>Bottom radius (nm)</th>
<th>( \sigma_P ) (nm)</th>
<th>( \sigma_L ) (nm)</th>
<th>( \sigma_H ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Ray</td>
<td>99.98</td>
<td>52.95</td>
<td>69.2</td>
<td>88.0</td>
<td>9.2</td>
<td>5.4</td>
<td>2.0</td>
<td>2.2</td>
<td>0.68</td>
</tr>
<tr>
<td>TEM</td>
<td>99</td>
<td>53</td>
<td>66</td>
<td>85.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
X-ray intensity simulation for metal covered structure

<table>
<thead>
<tr>
<th></th>
<th>Core</th>
<th>Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>100 nm</td>
<td></td>
</tr>
<tr>
<td>MCD / SW Thick</td>
<td>45 nm</td>
<td>4 nm</td>
</tr>
<tr>
<td>H / Top Thick and Bot. Thick</td>
<td>50 nm</td>
<td>6 nm</td>
</tr>
<tr>
<td></td>
<td>5 nm</td>
<td>5 nm</td>
</tr>
<tr>
<td>SWA</td>
<td>90 deg</td>
<td>87.5 deg</td>
</tr>
<tr>
<td>RB</td>
<td>5 nm</td>
<td>10 nm</td>
</tr>
<tr>
<td>RT</td>
<td>5 nm</td>
<td>10 nm</td>
</tr>
</tbody>
</table>

Metal: Ti
Application for DTM Profile Measurement

Top view

Incident x-ray
Rotation
Diffracted x-ray
2D-detector
Disk sample
Track line

120nm-pitch imprinted resist-tracks on a 65 mmφ magnetic disk coated with conventional perpendicular recording layers

Side view

Incident x-ray
\[ \alpha = 0.16^\circ \]
Diffracted x-ray
2D-detector

X-rays irradiate sample surface with grazing incident angle. Diffracted x-rays are detected by two-dimensional detector.
X-ray Diffraction Measurement of DTR Resist Pattern

Sample was provided by Hitachi

Diffraction pattern have been successfully detected even the track-line is curved.
Measured DTM Profiles by X-ray Profilometry

Resist can be damaged by electron beam irradiation of SEM

From x-ray diffraction

Table. Structural parameters of periodic grating profile

<table>
<thead>
<tr>
<th>P (nm)</th>
<th>H (nm)</th>
<th>L_W (nm)</th>
<th>θ_{SW} (degree)</th>
<th>R_T (nm)</th>
<th>R_H (nm)</th>
<th>αL</th>
<th>αP</th>
</tr>
</thead>
<tbody>
<tr>
<td>120.06</td>
<td>78.0±0.1</td>
<td>24.14±0.24</td>
<td>86.0±0.2</td>
<td>5.31±0.02</td>
<td>20.18±0.12</td>
<td>2.0±0.2</td>
<td>0.83±0.14</td>
</tr>
</tbody>
</table>

The tool uncertainty (3σ) is simulated as <0.2nm, beyond ITRS2019
X-ray Diffraction Measurement of BPM Pattern

Sample rotation are needed around the reciprocal axis

Average spacing

Fluctuation of the spacing
Simulation of X-ray Diffraction Intensity Distributions from BPM shapes

X-ray profilometry can measure the parameters like DTR pattern profiles.
Summary

1. Non-Destructive X-ray profile measurement method is available for BPM.
2. The X-ray Profilometry tool exhibit the ability of CD measurement with 0.2 nm(3σ) accuracy. This is beyond ITRS 2019.
3. X-ray Profilometry does not need standard because X-ray wave length is determined in the 8 digits.
4. Resist pattern is measured without damage comparing to electron beam measurement method (SEM).
5. Measurement time is currently 100 seconds for 1 point.
Thank You!

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