Overview of EUV Mask Metrology

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Lithography Scaling

The diagram illustrates the scaling of lithography over time, from 1970 to 2020. Key technologies include Lamp, KrF, ArF, and Plasma. The timeline shows the progression from 6.1 μm to EUV (Extreme Ultraviolet) technology.
EUV Lithography

• EUV masks and projection optics are reflective
  – Differs from conventional refractive optics use in production lithography systems
  – No optical materials are transparent for EUV

• Highly sophisticated mirrors
  – Mo/Si bi-layer coatings for high reflectance
  – Low surface roughness on the order of a few atoms
  – Stringent flatness and curvature requirements
  – Mask must have no resolvable defects
EUV Lithography and challenges

- First EUV tool installed in Albany
- EUV is real BACUS, EUV Symposium
- EUV Mask Consortium (EMI)

<table>
<thead>
<tr>
<th>Year</th>
<th>Defect-free mask</th>
<th>Source power</th>
<th>Resist resolution</th>
<th>Reticle protection</th>
<th>Optics quality</th>
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<td>2009</td>
<td>~ 100-500X defect reduction required for HVM</td>
<td>&gt; 100 W @ IF reliable source required</td>
<td>LWR needs 2-3X improvement for MPU (OK for Memory)</td>
<td>Commercial reticle-handling solution available in 2010</td>
<td>PPT optics being assembled; 3300 optics in development</td>
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Defect Reduction Needs/Plans

• For 22nm node:
  – Memory needs ~10 or less defects/blank @ 30nm size
  – Logic needs 0 printable defects at ~30nm size (~10 well-localized and repairable defects)

• Today, defects are at ~40 / blank @ 50nm size (defect density of 0.25/cm²)

• SEMATECH defect reduction roadmap:
  – 2011: 0 > 150nm; 0.13/cm² @ 50nm < x < 150nm
  – 2012: 0 > 100nm; 0.13/cm² @ 35nm < x < 100nm
  – 2013: 0 > 80nm; 0.13/cm² @ 35nm < x < 80nm
Fabrication of EUV mask

Mask fabrication process steps

Defect types
Defect categorization in EUV mask blank

- EUV masks are vulnerable to different types of defects
  - Amplitude defects: surface particles/pits that generate contrast changes at the wafer
  - Phase defects: bumps/pits at the substrate which become buried below the multilayer
    - Results in a phase change of the reflected wave.
    - Phase defects as small as 1 nm in height or depth can result in printable defect
Development of defect-free EUV blanks
SEMATECH’s EUV Mask Defect Analysis Approach

- **Defect inspection**
  - Inspection before and after ML deposition.

- **Failure analysis**
  - X-sectional and compositional analysis.
  - EDS and AFM have been the work horses for small defect analysis.
  - AES and TEM are necessary and recently established for even smaller defect sizes.
  - Enables isolation of defect source.

- **Defect printability**
  - Which defects will image in an exposure tool.
Substrate and Blank Inspection

Defect Detection
M1350 (488nm) / M7360 (266nm)
- Confocal microscope
- Defect review
- Punchmarking capability

- A champion EUV blank.
  - Few defects (41 pits, 10 particles) @ 50nm sensitivity.

- A typical good EUV blank.
  - Many more defects (about 100 pits, 15 particles, 71 not classified) at 50nm sensitivity.
FIB/SEM

- Anchor failure analysis (FA) tool
- Tool Configuration
  - 6” mask holder, manually load.
  - Automatic navigator by KLARF.
  - Oxford Instruments EDS.
  - Focus Ga+ ion beam.
  - Omniprobe.
- Supports
  - Compositional analysis of defects >100 nm.
  - TEM sample.
  - SEM imaging.
FIB/SEM and EDS Capability

- **FIB/SEM EDS analysis**
  - Adequate for chemical characterization of large size defects, >100nm.
  - But capability limited due to penetration depth of X-Rays.

- **SEM Imaging**
  - Low contrast of some defects creates challenges for locating defects in SEM.
    - Although optically detected.
    - Impacts location and TEM sample prep of these defects.
Atomic Force Microscope (AFM)

- Primarily supports
  - Imaging of particle and pit type defects on substrate and mask blank.
  - Surface roughness measurement.
  - Bonding force of particles and mask absorber.

- Capabilities
  - <0.09 nm RMS noise level
  - Depth repeatability
    - static – 1.0 nm (3s)
    - dynamic – 2.0 nm (3s)
  - Static Roughness repeatability of 0.05 nm for surface of 0.15-1.0 nm RMS
Auger Electron Spectroscopy

• Capacity for whole 6” masks
  – Eliminates contamination of cutting glass
  – Preserves coordinate system from inspection tool
  – Automatic full mask navigation

• High resolution
  – 6 nm SEM resolution
  – 8 nm Auger resolution

• Tilted electron column
  – Capable of analyzing both top surface and cross section without tilting stage
AES Validation of EDS Data from FIB/SEM

- It is difficult to separate Cr from O due to overlapping EDS peaks.

- Auger spectra confirm the defect contains Cr. They also indicate there is no Mo on the analyzed surface.
AES: Small size defect analysis

- Auger map shows the distribution of C and Si elements.
- The example confirms defects of 30 nm size can be analyzed on conductive surfaces.
AES: Cross-sectioned defect

- Buried defect was exposed by a vertical FIB cut.
- Auger maps reveal detail information.
  - Defect contains highly oxidized Al.
  - Defect contains Fe, which is not clustered.
  - The C defected by EDS came from Pt deposition.
  - There is N distributed uniformly in Si/Mo film.
AES: Defects on non-conductive SiO$_2$ substrate

- Surface charging is constantly challenging for AES analysis especially when high voltage and small spot size are applied to small defects.
- A carefully controlled conductive coating is used as a counter measure.
- The example shows a defect containing C. The conductive coating is thin enough that Auger electrons can escape. Meanwhile it has to be thick enough to dissipate surface charge.
Titan S/TEM

- Increased imaging and analysis capability due to $C_S$ probe-corrector and monochromator.
- Flexibility in accelerating voltage (80-300kV).
- Spatial resolution: 70pm.
- Point resolution: 80pm.
- Environmental closure reduces noise from environment.
- New X-FEG electron gun yields maximum source brightness and beam coherency.
- Triple condenser system for flexible illumination.
- Detectors: On-axis triple DF1/DF2/BF and HAADF.
Energy dispersive x-ray spectroscopy (STEM-EDS)

Elemental mapping through EDS provides a fast and comprehensive composition analysis of EUV mask blank defects.

FEI SuperX upgrade coming Spring 2011

- Windowless detector can detect elements down to and including Boron.
- 4 silicon drift detectors (SDDs) integrated into objective lens for large collection angle.
- High sensitivity for even low-intensity signal.
- Fast elemental mapping and spectroscopy acquisition.
Imaging modes HR-TEM

- Crystallinity information can be derived

- Crystalline Si defects originated from Si target during deposition
Imaging modes HR-STEM

- High angle annular dark field (HAADF) imaging: highly scattered electrons are collected for z-contrast.
  - Provides details of multilayer film growth over substrate and embedded defects.
Other analytical techniques on the Titan

• Energy filtered imaging and electron energy loss spectroscopy (EELS)
  – Energy filtered imaging, EELS, and EELS mapping will provide unprecedented compositional analysis for sub-50nm mask blank defects.
  – Resolution is limited by sample thickness, so we are restricted by our current sample preparation techniques.

• 3D tomography
  – Tomography holder allows 40 rotation for accurate 3D reconstructions.
  – Shape and size information can further advance SEMATECH’s defect reduction program.
Phase Defect Detection

- Phase defects
  - Defects buried below the multilayer
  - Difficult to consistently detect using current blank inspection and mask inspection systems.

Source: Ken Goldberg
Defect printability

- Disruption in multilayers provide phase defects and hence intensity contrast, even though the surface on top appears smooth.
Non-Actinic Tool vs. Actinic Tool

- Non-Actinic inspection will have limitations
  - Low contrast images in SEM fully resolve with EUV imaging and become printable
  - Other defects are detected but are transparent to EUV radiation
Defect Detection with Non-Actinic Tool

- Invisible with SEM and optical review
- But printed on wafer…and see with AIT

Source: Rik Jonckheere et al, EMLC 2011, SEMATECH AIT
High Level Requirements for Actinic Blank Inspection

• **Inspection requirements:**
  – Substrate pits/bumps (phase defects) must be detected & localized.
    • Size: ~35nm FWHM x 0.7nm height.
  – Particles, even just under the capping or top multilayers (amplitude defects) should be detected & localized.
    • Size: ~15nm FWHM x material dependant depth.

• **Classification and review requirements:**
  – Review should accurately localize the defects so mitigation by pattern shifting can be used.
    • Alignment needed ~15nm.
  – Defects should be classified, and near the sensitivity limit, we should review them to know if signals will print or impact patterning.
    • Diffraction limited aerial image which approximates the scanner
EUVL Mask Process Flow

- A mask process flow with gap tools shown using red outlines. Several clean steps not shown.

Why classify/review and localize defects?
- Localization and pattern shifting could save blanks from being scrapped.
- We classify defects today and need to continue this when operating at the sensitivity limit where false positive/negative defects are a way of life.
- Non-repairable substrate/multilayer defects must not cause yield loss at pattern mask inspection. Yield is a strong cost/cycle-time driver for mask shops.
Future EUV Mask Metrology Needs

• 30nm defects are relevant for the 22nm hp node, and defects as small as 10nm may print in the next few years…

• The industry needs:
  – Actinic blank inspection with defect location of ~few nm
  – AIMS review capability to support 11nm hp and beyond
  – Advanced patterned mask inspection to 11nm hp & beyond
  – Chemical characterization methods for 10nm defects
EMI status overview:

- **Blank Inspection (BI)**
  - Japan’s EIDEC supporting with Lasertec BI effort
  - Will not meet logic manufacturers’ needs, so improvement required

- **Patterned Mask Inspection (PMI)**
  - SEMATECH supporting KLA-Tencor actinic PMI program (7xx)
  - Multiple e-beam PMI suppliers have emerged (AMAT, HMI, others)

- **AIMS**
  - Program proceeding, but final signatures still needed from some members

- **Metrology source development**
  - EUV sources for actinic metrology require improvement from 8W mm$^2$ sr to ~100W mm$^2$ sr
Summary

- SEMATECH’s EUV mask defect reduction efforts are grounded in metrology
  - Comprehensive (and still growing) suite of inspection and characterization equipment
- Inspection and characterization for defects <30nm pose critical challenges for the metrology industry
- EMI is an organization creating financial pathways to support the development of infrastructure solutions for these challenges