Optical Digital Profilometry Test Patterns, Database, and Strategy

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Collaborative FLCC Experiments

Original Experiments

Optical Digital Profilometry (ODP)

FLCC Experiments

Designs from industry

FLCC

April 16th, 2007
Outline

• New set of masks from Toppan and experiments at SVTC with the help of ASML

• Web accessible database for data aggregation and analysis

• Optical Digital Profilometry

• New Defocus Test Structures

• Measuring Mask Edge Effects

• Illumination and 2-D Patterns

• Conclusion
New Company New Process

Cypress

65nm CMOS Flow

SVTC
Silicon Valley Technology Center

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New Company New Process

Cypress

65nm CMOS Flow

SVTC

Silicon Valley Technology Center

Developing new vanilla CMOS flow

- No Cypress customizations, so more representative
- More synergy and direct benefit for SVTC translates to more wafers

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Old Test Chip Layout

- Over 15,000 Electrical Test Structures
- Six students, six sets of conclusions, one chip

178 30-pad cells

Cypress Test Structures

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Cypress Test Structures

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New FLCC06.v2 Chip

- 21 extra 30-pad cell structures (199 total)
- 256 gratings for Optical Digital Profilometry (ODP)
- Two more students and three companies contributing
4 Layers Per Mask

1mm x 1mm block

9X

8 450um x 220um gratings
3mm x 2mm block

4 Layers Per Mask

48 450um x 220um gratings
Space Available on Dark Field Mask

- Atten PSM + 90 degree phase etch
  - Mosi or Chrome
  - Glass can have extra 90 degree etch

All four layers available

Thirty-Two 1mm x 1mm blocks

Four 2mm x 3mm blocks
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Tons of Test Structures, Tons of Data, One Chip

Looking at

- Systematic CD variation
- LWR
- Defocus
- Enhanced Transistors
- Contact hole variation (correlate with pattern noise work)
- BSIM model fitting
- Oxide thickness and channel doping

- Poly corner rounding
- Active corner rounding
- Non-rectangular transistors
- Poly overlap
- Electrical Overlay Error
- SRAMs and Standard Cells
- Poly Etch
- Poly CMP
- Mask edge effects
Tons of Test Structures, Tons of Data, One Chip

Looking at

- Systematic CD variation
- LWR
- Defocus
- ETEC-M validation
- Contact hole variation (correlate with pattern noise work)
- BSIM model fitting
- Oxide thickness and channel doping

- Poly corner rounding
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Data Management Nightmare

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Relational Database for Data Aggregation

- Over 15,000 transistors, 150 die per wafer, and dozens of wafers

- Slice and dice the data in any way
  - Each data point will be associated with many different tables
  - Comparing simulation and experiment results
  - Finding Correlation
    - Can find correlation between transistors with specific attributes such as proximity or distance from center
  - Looking at subsets of test structures
  - Filtering out confounding effects (systematic CD variation)

- Platform for Collaboration
  - Each designer can access and update the database online
  - Outside people can log on as guests and explore different pattern dependent phenomena
Store All Possible Data

What else should I look at???
Web Accessible and Centrally Located

**Probe Station**

- Download test scripts
- Upload test results

**Server**

- Update database with calculated process offsets
- Download data for analysis
- Access any data through SQL queries or pre-built filters
- Run some basic statistical analysis

**Designers**

- Upload results for others to see

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The goal of scatterometry is to measure the geometry of fine lines nondestructively with light.
Simulated vs. Measured Results

Goodness of Fit (GOF) – Indication of best match.
1 is best, 0 is worst. Typical iODP100 GOF > 0.995

Note: Red spectra is simulated and blue is measured
1. (n,k) values can be determined on Sopra, or from standard table.
2. Spectra will be collected on Sopra. Data need to be interpreted in the form that can be read by Timbre ODP TeraGen.
3. This is what we have from Timbre.
4. Only for volume production.
Step 1: Thin Film Data Collection (Recommended)

The index of refraction, $n$, and the absorption coefficient, $k$, are different for different materials, and vary as a function of wavelength.
Step 2: Collect and Import Data of Patterned Wafer

Spectral Data
Step 3: The Profile Model

(1) Diameter of hole at oxide layer;
(2) Diameter at the bottom of the etched hole;
(3) Thickness of Anti-Reflective Coating (ARC);
(4) Thickness of dielectric layer;
(5) Thickness of Silicon Carbide (SiC);
Step 3: The Profile Model

(1) Diameter of hole at oxide layer;
(2) Diameter at the bottom of the etched hole;
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Model Verification

Rigorous Coupled Wave Analysis (RCWA)

\[ \sum_{t_n} \text{for } \theta, \lambda \]
Model Verification

Rigorous Coupled Wave Analysis (RCWA)

Forward Simulation

Incident Light

\[ \sum_{t_n} \text{for } \theta, \lambda \]
Model Verification

- Results are sensitive to feature (CD) of interest
- Results agree with reference metrology
- Parameter ranges are sufficient to cover process variation
- Parameter correlations are avoided
Step 4: Library Generation and Verification

• Based on the confirmed model (parameter)
• RCWA simulation generates the library

![Diagram showing the flow of library generation and verification process]
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Resonant Even Aberration Testing Mask

- Periodic testing pattern,
- Probe width provides reference 25% CF magnitude:
  \[ w_b(\lambda / NA) = \frac{25\%}{\sqrt{8.5}} \approx 0.3 \]
- Probe phase coherent to even (defocus) aberration
- Pattern width equal to minimum feature size
- Distance \( d \) determines the sensitivity of this aberration and the orthogonality to the other aberrations
Line Spread Function vs. Aberration

- Defocus
  - 0.01817

- Spherical
  - 0.02314

- Coma
  - 0.05831

Reference
- 0.01451
Resonant Even Aberration Testing

- Inverse Fourier transform of even aberration based on line spread function
- Reciprocity of the electric-field spillover
Resonant Even Aberration Testing

Sensitivities of defocus and spherical target are at least 28 times larger than the Strehl ratio measurement of aberration at $0.01\lambda$ aberration

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Defocus Monitoring + ODP Calibration?

pos-resist

neg-resist
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Mask Edge Effects

- Phase Shifting Mask Opening Cross-Talk
  - Use TEMPEST time-evolution to visualize cross-talk as it occurs among masks openings
  - Introduced reduced parameter edge and line source models
Simple Mathematical Model for 2\textsuperscript{nd} order Fourier component

For 50% duty cycle

\[ \int_{box} e^{j \frac{2\pi}{P} x} = 0 \]

\[ \int rect \times e^{j \frac{2\pi}{P} x} = 2w \]

This value are the quantities \( C_{ER} \) and \( C_{ER} \) for the real and imaginary correction components.

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Intuition

E Field

Im(E)

Horizontal Shift: $C_{ER}$
Vertical Shift: $C_{CEI}$

Mag(E)

Mag(E) actual

Mag(E) ideal

Re(E)

Mag(E) (ideal box)

Mag(E) (actual)

Duty Cycle

$\Delta f$

50%

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Simulation Results

Cutline taken far from interface in order to analyze propagating modes.
2nd order component of TE mode

Walls undercut 5 degrees

Vertical Walls

Expect 2nd order to go to zero

Period
Magnitude → Zero
Minimum → 50% Duty
Simulation Values for $C_{ER}$ and $C_{EI}$

$C_{EI} = \frac{E_{\text{min}}}{\text{Period}}$

$C_{ER} = \frac{\Delta f}{\lambda} \frac{\text{Period}}{\lambda}$

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Experiment: FLCC March ‘07 Mask

• Gratings put on current FLCC mask to explore simulation results
  – Alternating 0° and 180° phase shift regions
  – 4 periods ranging from 3 to 12 λ (on mask)
  – Duty cycle ranging from 35-65%
  – 24 different gratings in total

• Compare data from these gratings to the TEMPEST simulations
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ODP Illumination Test Patterns

Binary Mask Example

Normal Incidence

P = 1.7λ/NA

Center line not print

Spillover Subtracts

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ODP Illumination Test Patterns

Binary Mask Example

\[ P = 1.7\lambda/NA \]

\[ s = 0.59 \text{ dipole} \]

Spillover Adds!

Center line prints!
A richer set of combinations are allowed by
• Phase-shifted openings
• Using spillover from a sizeable 1RU+ programmed focus offset
  example $P = 1.2\lambda/NA \Rightarrow s = 0.83$ dipole
ODP 2-D Test Patterns are Better

Binary Mask Example

- More Flexible: spillover separation and illumination phase can be adjusted somewhat independently.

$r = 0.85 \lambda / NA$

$\sigma = 0.45 \lambda / NA \Rightarrow 0.9$ dipole
Optical Digital Profilometry Test Patterns, Database, and Strategy:

Conclusion

• We have been able to respond quickly in generating a new multi-student test mask for automatic measurement and profile recognition with ODP.
• The clear field mask includes line patterns. Phase-shifting patterns will be put on the dark-field mask that tapes out soon.
• A database is also proposed for assembling and cross-interpreting ODP results.
• Monitoring concepts from pattern-and-probe test patterns and electronic test patterns have been used to generate novel ODP-based parameter specific monitors for focus, illumination, and mask edges.