Faculty Presentation: Lithography

By Andy Neureuther, Costas Spanos, Kameshwar Poolla, EECS and ME, UC Berkeley
Current Milestones

- **Litho 1**: Develop and experimentally verify process effect monitoring and full chip assessment methodologies
  - Lynn Wang: Parameter specific RO layout and simulation
  - Eric Chin: Through-focus interconnect models and link to SPICE

- **Litho 2**: Electromagnetic modeling methods and electromagnetic phenomena
  - Marshal Miller: Mask edge effects 2D and 3D and link to design
  - Dan Ceperley: Plasmon generation efficiency and Laser Spike Anneal

- **Litho 3**: Fast-CAD for full process window characterization of double patterning and guidance during decomposition
  - Juliet Rubinstein: Through-focus Pattern Matching and DP decomposition
  - Alex Li and Jihoon Kim: LAVA website repair and update

- **Litho 4**: Assessment tools for double patterning decomposition
  - State dependent learning to maximize process window

- **NT 4**: ODP-based parameter extraction and silicon verification
  - Optimized dual period 1-D gratings for optical aberration extraction
Parameter Specific Electronic Monitors

Goal: Use process/device/circuit simulation to understand process variation electrical contributions and develop parameter specific electronic monitors

- Lateral interactions between standard cells using pattern matching (BACUS 07)
- Hyper-Sensitive Parameter-Identifying Ring Oscillators for Lithography Process Monitoring (SPIE 08)
- Layout and simulation of monitors for 45 nm process (BWRC)
  - Focus Poly
  - Active focus with poly to active alignment
  - Etch
  - Stress: S/D and STI

with Lynn Wang
The Berkeley Wireless Research Center (BWRC) and ST Micro are providing silicon at 45 nm and ring-oscillator testing in return for simulation assistance in diagnosing various sources of variation in circuit performance. The project is lead by Professor Bora Nikolic and the collaboration includes students of Professor Costas Spanos and Tsu-Jae King.
Ring Oscillator Array Layout: 45 nm Chip

- Test Structure = Tile
- 32 Tiles = 1 BigTile
- Vertical Scan-Chain
- Horizontal Scan-Chain
- Muxes 32 rows into 1 output
- Divider
- Die Area (2mmx1mm)

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Interconnect Variation Sources and Monitors

Goal: Use process/device/circuit simulation to understand process variation electrical contributions and develop parameter specific electronic monitors.

- Prediction of interconnect delay variations using pattern matching (SPIE 07)
- Modeling timing across the lithographic process window (SPIE 08)
  - Process Variation Net Scanning (PVNS) TCAD tool
  - Tested prototypical interconnect scenarios
  - Focus monitor based on PSM edge shift
  - Bossung plot for R, C and delay (=> F-E algebraic model)

Eric Chin
SRC-Intel Fellowship

with SRC® 1443
Semiconductor Research Corporation

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Process Variation Net Scanning

- Bypass rigorous litho simulation using pattern matching approximations (speedup > 1000x).
- Initial results (2006) show general trend from automated simulations and CD measurements.
- Fitted curves allow for a fast method to approximate response of CD to different aberrations using Pattern Matching.
- These CD changes are translated into deltas in extracted parasitics, and ultimately timing.

2008 Goal: Improve Model Accuracy
Bossung behavior suggests Algebraic Model

Double Patterning

Two lateral patterning steps are required for each metal layer. Misalignment from one patterning step to another may skew capacitance and affect timing.

Focus-Exposure Algebraic Models

Algebraic models for through focus behavior can be used to identify tradeoffs between wire placement and delay minimization.
Electromagnetic Modeling

- Goals: Characterize ATT-PSM edge effects, explore plasmon monitors, and examine speed-ups in simulation and interpretation of signals in mask and wafer inspection.

  - Characterization and monitoring of photomask edge effects (BACUS 07)
  - Impact of Photomask Quadrature Edge Effects through Focus (SPIE 08)
    - Modeling mask material effects
    - Modeling jogs through focus
    - Candidate thin-mask models and optimization for 2D patterns
    - Characterization of narrow mask feature effects
    - Enabling Pattern Matching for assessing mask edge effects during design

Marshal Miller
Special Characterization of Narrow Mask Features

- 22nm node leads to 88nm (4x) mask features (50nm reported at BACUS)
  - Films 50-100nm (MoSi ~70nm)
- E parallel low phase
- E perpendicular low amplitude
- Crosstalk significant

\[ \theta = \cos^{-1}\left(\frac{n_1}{n_2}\right) \]

- MoSi-Air: \( \theta = 65.7^\circ \)
- MoSi-\( \text{H}_2\text{O} \): \( \theta = 51.9^\circ \)
Enabling Pattern Matching for Assessing Mask Edge Effects in Design

- Add boundary layers to layouts and test imaging, hotspot detection
- Generalize pattern matcher for complex mask layouts
- Perform matching with complex kernels (focus) and complex rectangles
- Verify worst case locations with rigorous (thick mask) image simulation
- Establish a through focus algebraic model for mask edge effects
EM Simulation Framework

Goal: Provide cross-cutting EM simulation capabilities to guide technology innovation in maskless and emerging lithography issues.

DARPA/SRC Project and Dan is on FLCC/IMPACT Spring 2008 to assist Litho 2 (EM simulation)

- Developed TEMPEST v7 to provide computational and physical insight to optoelectronic, plasmonic, lithography and laser anneal

- New computational capabilities include:
  - Half-cell material boundary placement control
  - Pulsed, surface plasmon, and induced polarization sources
  - Post-processing device under test system

- Applications include:
  - Bloch-wave view of Sub-Wavelength Grating
  - Plasmonic couplers, nanoparticles, and lithographic mask elements
  - Rapid Thermal Annealing

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Quantitatively Engineering Novel Optical Devices Through Computer Simulation

Signal Flow model for finite length grating plasmon generation and validation

Characterization of Optical Spike
Annealing of metal gates

PICTURE DESCRIPTION

Plasmon Output from 6 Bar Grating

Hz Amplitude (664nm Pitch)

Reflection
Gate
Transmission

Si Wafer

500 nm Capped 0 deg
-500 nm Capped 90 deg
800 nm Capped 0 deg
800 nm Capped 90 deg
10 um Capped 0 deg
10 um Uncapped 0 deg
Gate Variation Sources and Monitors

Goals: Develop fast approximate methods with physically based models to assess and guide decomposition for double patterning and spacer lithography and develop parameter specific electronic monitors

Intel Fellowship with Juliet Rubinstein

- Images in Photoresist for Self-Interferometric Electrical Image Monitors (BACUS 07) {based on double exposure, open/short}
- Post-Decomposition Assessment of Double Patterning Layout (SPIE 08)
  - PV-band vs. PM shows proximity and focus are distinct
  - Defocus OPD^2 => PM with Z_0, Z_3, Z_9 Now Works!
  - Pre-OPC PM and Post-OPC PM similar but some differences
  - Testing on IMEC-SPIE layouts and alternative splits
Matching with Z0, Z3 and Z8 Patterns

Z0 Pattern

Z3 Pattern

Z8 Pattern

Il at pupil  Il at mask  Focus at mask  IL x Focus at mask

Note: Summer work by Anthony Yeh and Lilly Kem allows off axis pattern generation
New Through-Focus Correlation Plot

\[ E(x_{ow}) = \int \int \int e^{j\bar{k} \cdot \bar{x}_{mask}} / M e^{-j\bar{k}_{illum} \cdot \bar{x}_{mask}} / M \left[ 1 - j\text{OPD} - \frac{\text{OPD}^2}{2} \right] e^{-\bar{k} \cdot \bar{x}_{ow}} rd\phi dr \]

\[ \text{OPD}^2 = (1/3)Z_0 + (2/3)Z_8 \]

- Linear model with \( Z_3^2, Z_0 \) and \( Z_8 \) fits!
- Fitting coefficients are track the square of the rms defocus level

Defocus 0.048 rms waves  
\( R^2=0.92 \)
Fast-EM Methods for EUV Masks


This work is supported by Intel and will provide a leg-up for IMPACT in Y3 and Y4.

- Fast Three-Dimensional Simulation of Buried EUV Mask Defect Interaction with Absorber Features
- Smoothing based model for images of isolated buried EUV multilayer defects (SPIE 08)
- Interpretation of at wavelength inspection of buried defects, (with Sandy Wirtaamadja and Tina Chan) EUV Symposium
- Smoothing Based Model for Images of Isolated Buried EUV Multilayer Defects (BACUS 08)

Chris Clifford

Simulation with aberrations

LBNL Goldberg Experiment

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Printing Assessment and Scatterometry Calibration of Probe Pattern Grating (PPG) Focus Monitor

- Jing Xue, Andrew R. Neureuther and Costas J. Spanos
Design of PPG Focus Monitor

Defocus pupil OPD

First side-lobe: 0.45 $\lambda$ /NA
Second side-lobe: 1.2 $\lambda$ /NA
**Design of PPG Focus Monitor (cont)**

\[ P = 0.9 \frac{\lambda}{NA} \]

\[ P = \frac{\lambda}{NA(1-\sigma)} \]

**Mask Plane**
- + 1 order
- 0 order
- -1 order

**Pupil Plane**
Focus Monitor Sensitivity

Sensitivity vs. Pitch

* $\sigma = 0.1$ circular illumination

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Design of PPG Focus Monitor

Aerial image of PPG with defocus
Aerial Image of PPG Focus Monitor

Sensitivity of PPG focus monitor

Defocus (R. U.)

Intensity

slope = 0.316
slope = 0.402
slope = 0.512
slope = 0.671
slope = 0.843
Resist Image Characterization

Probe-pattern line behavior through defocus
Scatterometry Measurement Results

Probe trench depth vs. defocus for vertical gratings

<table>
<thead>
<tr>
<th>Dose (mJ/cm²)</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope (nm/RU)</td>
<td>84.7</td>
<td>93.1</td>
<td>106.1</td>
<td>106.1</td>
<td>105.9</td>
</tr>
</tbody>
</table>
Scatterometry Measurement Results (cont.)

Probe trench depth vs. defocus for horizontal gratings

<table>
<thead>
<tr>
<th>Dose (mJ/cm²)</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope (nm/ RU)</td>
<td>94.2</td>
<td>92.8</td>
<td>100.5</td>
<td>104.3</td>
<td>105.6</td>
</tr>
</tbody>
</table>
Estimated average field astigmatism variation along scanner slit direction
Clip Calculus (contd!)

- **Justin Ghan + Poolla, Neureuther, Spanos**
- **Basic Assertion:**
  Working with clips is more efficient and natural than distances/rules
- **Potential opportunities for clip calculus**
  - Faster printability analysis
  - Inverse Litho
- **Clips**
  - Could be non-rectangular
  - Standard cells, macros, etc …
  - Core “Central” part of a clip
  - Context “Outer” part of a clip
  - Library Collection of clips
- **Core & Context depend on target application**
  - Ex: DRC, OPC, Printability analysis
- **The problem: algorithms to efficiently deal with clips**
Current Practice
  - DRC brick is 2,000 pages and exploding, Conventional rule-based DRC at 22nm will be unmanageable

Alternatives: Work with clips not distances
  - Leverage the speed of pattern match
  - Produce library of good, bad, or graded patterns
  - Use library to detect and correct new design layouts

Open problems
  - Clip-based DRC, Hybrid Rule-Clip DRC,
  - Redundancy removal in rules, Correction!

Core and Context
  - Core is the region that is DRC clean given the fixed Context
  - Context may not be DRC clean as that depends on Context(Context)

Use Case
  - Library of known DRC clean (in core) clips
  - In a mask M, use PatternMatch against library L
  - Can eliminate the core of every matched clip
  - Will have to do DRC on remaining areas
Field-Stitching for Inverse Litho

- Lithography operator is a **spatial low-pass filter**
- Library L consists of **pairs** $\pi = (C, t)$

The clip $C$ on a mask will print the target image $t$ **independent** of the what else surrounds $C$

- Many **different** clips can print the **same** image $t$
- Library L is easy to generate with a litho simulator
- Given a target layout $T$, can we **continuously** tile it with clips from the library?
Continuous tiling

- **1-d case (easier to visualize)**
  - Library pair $\pi = (C, t)$
  - $C$ looks like [L M R] and produces $m$ on silicon
  - Many $C$ produce same $t$
  - Target layout $\{t_1 \, t_2 \, t_3\}$

- **Problem:**
  - Choose 3 library elements of the form $([a \, b \, c], t_1), ([b \, c \, d], t_2), ([c \, d \, e], t_3)$
  - Then the mask $\{a \, b \, c \, d \, e\}$ will produce the image $\{t_1 \, t_2 \, t_3\}$

- **This is a di-graph optimization problem** related to DNA sequencing methods
Graph Optimization

- **Library Directed Graph**
  - Constructed from library

- **Clip graph**
  - Nodes are clips
  - **Red edges** from \([a \ b \ c]\) to \([b \ c \ \cdot]\)

- **Image graph**
  - Nodes are images \(t\)
  - **Blue edge** from clip to corresponding image

- **Optimization problem:**
  Given a path of images
  Find any corresponding path of clips restricted by the graph
Continuous tiling

- **2-d continuous tiling**
  - Harder to visualize
  - Easy to generate Library Graph using pattern match
  - Need to allow for approximate tiling also

- **Will this work?!**
  - Don’t understand time and space complexity of algorithm
  - How big a library do we need?
  - Probably has a chance for XRDR (extremely restricted design rules)
  - Or maybe for contact masks

- **Key issue: how many distinct clips occur in a mask?**
  - If there are too many “types” of clips, we are in trouble
  - Tool for answering this question: clustering

- **2008 Goals**
  - Devise and analyze algorithms for basic clip operations
  - Test clip-based DRC on modest layout for speed-up
Collaborative Verification Discussion

Sandboxes
- Berkeley Microlab
- BWRC DATA
- Industry Data
- SVTC via ASML
- Industry tools
- Industry CMOS
  - SVTC via ASML
  - ST Micro via BWRC
  - IBM?
  - Foundry via Marvell?

Investigations
- Collab. Platform DfM
- Tool SEM impact to device
- Cell-to-Cell Interactions
- Double Patterning
- ODP Aberrations
- Hyper-sensitive layouts
- RO for focus
Future Milestones

- **Litho 1: Process effect monitoring and full chip assessment**
  - Lynn Wang: Parameter-specific RO process monitors and sim
  - Eric Chin: Interconnect DP issues; F-E model; PVNS link

- **Litho 2: Electromagnetics**
  - Marshal Miller: Model narrow and 3D mask features

- **Litho 3: Fast-CAD for double patterning**
  - Juliet Rubinstein: apply $Z_0, Z_3, Z_9$ F-E model to DP
  - Alex Li and Jihoon Kim: Linux LAVA and advanced tech. Applets

- **Litho 4: Assessment tools for double patterning decomposition**
  - TBD: Explore application dependent clip weightings