PYRAMID: A Hierarchical Approach to E-beam Proximity Effect Correction

Soo-Young Lee
Electrical and Computer Engineering
Auburn University
leesooy@eng.auburn.edu
Presentation

- Proximity Effect
- PYRAMID Approach
- Exposure Estimation
- Correction
  - Shape Modification
  - Dose Modification
  - Heterogeneous Substrates
- Recent Developments
  - Grayscale Lithography
  - Non-rectangular Features
Lithography

• Optical lithography

• Electron-beam lithography
  – Direct-write
  – Throughput
  – Single or multiple beams
Terms

- **Dose**
  Energy given to a point (pixel)

- **Exposure**
  Energy deposited at a point (pixel)

- **Critical point**
  Point at which exposure is to be estimated
Proximity Effect - PSF

- Electron scattering
  - Forward
  - Backward
- PSF (Point Spread Function)
  - Beam energy
  - Substrate
- Blurring in the written pattern
  → Proximity effect

Energy Deposition Profile, 500 nm PMMA on Silicon

Exposure (eV/μm³ - electron)

Radius (μm)

50 KeV
Proximity Effect - Model

- Space-invariant linear system
- \( g(i, j) = h(i, j) * f(i, j) \)
Proximity Effect – *Etec Pattern*

- Minimum feature: 0.1 $\mu m$
- Circuit size: $50 \times 50 \mu m^2$
- High density
Proximity Effect - Example

- A center region of the Etec pattern
- 500 nm PMMA on Si, 50 KeV
- Lift-off (Au)
Proximity Effect Correction

\[ g(i, j) = h(i, j) \ast f(i, j) \]

- Modify \( f(i,j) \) \( \Rightarrow \) modify **shape** or **dose**
  \[ s.t. \ f''(i,j) \ast h(i,j) = f(i,j) \]
History of PYRAMID

- **PYRAMID approach**: hierarchical and look-up table
- Shape modification
- Heterogeneous substrates
- Neural network
- Hierarchical pattern representation format
- Dose modification
- Grayscale lithography
- Distributed processing
- Non-rectangular features
Issues in Proximity Effect Correction

• Accuracy
• Speed
PYRAMID Approach

• Hierarchical approach to exposure estimation and correction
  – Exposure estimation
    Local exposure and global exposure
  – Correction
    Local correction and global correction

• Look-up tables
  – Fast and accurate
Exposure Estimation

- **Local exposure:**
  - exposure contributions from the features (regions) close to the critical point
  - calculated by the exact and fast CDF (cumulative distribution function) table method
  - time-consuming due to the large number of regions

- **Global exposure:**
  - exposure contributions from the features located “far” from the critical point
  - calculated by a coarse grain convolution where a pixel is a global exposure block
Exposure Estimation – *Local Exposure*

- **CDF (Cumulative Distribution Function)**

\[ C(k, l) = \sum_{i=0}^{k} \sum_{j=0}^{l} P(\sqrt{i^2 + j^2}) \]

where \( C(k, l) \) is the exposure contribution from a rectangle of size \( k \times l \) to the critical point which is at the lower-left vertex of the rectangle and \( P(r) \) is the energy deposition profile.

\[
\begin{align*}
Exposure &= C(k_2, l_2) - C(k_1, l_2) - C(k_2, l_1 - 1) + C(k_1 - 1, l_1 - 1)
\end{align*}
\]
Exposure Estimation – *Local Exposure*

- Complexity of computing exposure contribution from a rectangular feature of size $K \times K$
  - The CDF table approach
    \[ O(1) \]
  - A conventional approach
    \[ O(K^2) \]
Exposure Estimation – *Global Exposure*

- **Coarse circuit image**: block-wise circuit area distribution

- **2-D PSF**: energy deposition profile sampled at the interval of block size
Correction – **Shape Modification**

- **Correction Hierarchy**
  - Each rectangle is replaced by its IMR (*Inner Maximum Rectangle*).
  - IMR’s and junctions are adjusted through iterations.

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Local correction

- IMR replacement

Global correction

- Junction adjustment
- IMR adjustment

- acceptable
  - No
  - Yes
Correction – *Shape Modification*

- **IMR Replacement**
  - Each rectangle is replaced by its IMR (*Inner Maximum Rectangle*).
  - IMR’s and junctions are adjusted through iterations.
Correction – *Shape Modification*

- **IMR Adjustment**
  - Each side of IMR is adjusted based on the *exposure estimate* at the corresponding *critical point*.

Adjust IMR edges such that the exposure at each critical point goes below the development threshold

Result after exposing IMR adjusted pattern
Correction – Shape Modification

- Junction Adjustment
  - The size of the removed square is adjusted based on the exposure estimate at the corresponding critical point.
Correction – Shape Modification

- Experimental Results *(CNF)*

500 nm PMMA on Si, 50 KeV, Gold lift-off
Etec pattern with MFS of 0.1 um

Uncorrected *edge region*

Corrected *edge region*
Correction – *Shape Modification*

- **Experimental Results** (*CNF*)

  500 nm PMMA on Si, 50 KeV, Gold lift-off
  Etec pattern with MFS of 0.1 um

![Uncorrected center region](image1)

![Corrected center region](image2)
Correction – Dose Modification

• **Correction Hierarchy**

  - Circuit features are partitioned for spatial control of dose within each feature.
  - Dose factor for each region is determined through iterations.

**Circuit Partitioning:**
- Feature Partitioning
- Rectangle Partitioning

**Exposure Estimation:**
- Global Exposure
- Local Exposure

**Dose Calculation:**
- Center, Edge, Corner, and Junction Regions

**Termination Condition**
- Yes: Store results
  - **No**
Correction – *Dose Modification*

- **Feature Partitioning**
  
  (A) A rectangle (feature) with multiple junctions
  
  (B) A large rectangle
Correction – *Dose Modification*

- **Rectangle Partitioning**
  - Each rectangle is partitioned into regions (*center*, *edge*, and *corner* regions) for spatial dose control within the rectangle.
  - Each region is assigned one or two critical points.
Correction – *Dose Modification*

- **Simulation Results** (Sequential vs. Simultaneous)

  Etec pattern of *50umx50um, 1000 nm PMMA on Si, 50 KeV*

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Heterogeneous Substrates
- Region-wise Correction

(A) A feature lies over two different regions.
(B) Each part is corrected with the corresponding PSF.
(C) An *intermediate segment* is set in the transition zone.
Heterogeneous Substrates
- Simulation Results

Ring width of 0.1 um
50 KeV

PMMA thickness (nm)

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Ring pattern
Uncorrected
Homogeneous correction
Heterogeneous correction
Recent Developments

- Grayscale Proximity Effect Correction
- Non-Rectangular Features
Grayscale Lithography

- PBG crystals, DOE, etc.
- A circuit pattern (structure) contains multiple levels.
- Exposure within each feature is to be uniform.
- *Ideal exposure* (corresponding to etch depth) for each feature

1. Expose
2. Develop
3. Etching
Grayscale Lithography - Region Partitioning

- (a) Fixed partitioning: may lead to unnecessary partitions
- (b) Simple adaptive partitioning: simple and effective
- (c) Deconvolution-based adaptive partitioning: higher adaptability but larger errors sometimes
Grayscale Lithography - Simulation
Grayscale Lithography - *Experiment*

Cross-section of remaining resist profile

J. Kim and D. Joy, UT Knoxville
Non-Rectangular Features

• Most proximity effect correction schemes assume rectangular features only.

• Circuits (e.g., PBG crystals, bus lines, etc.) contain non-rectangular features such as circles, rotated rectangles, polygons, etc.

• Efficient methods to handle such features are necessary.
Non-Rectangular Features
- Hierarchical Approach

Non-rectangular feature

Partitioned into correction shapes

yes

Basic Shapes ?

no

Partitioned into basic exposure shapes

A set of basic exposure shapes

“Basic shapes” : Right triangle, Rectangle, and Circle
Non-Rectangular Features
- Exposure Estimation:

**Direct Method**

- Circle and Ring
  Exposure contribution from a circle or ring is derived from CDFC table.

- CDFC table
  \( CDFC(d, r) \): exposure contribution from a circle of which radius is \( r \) and whose center is at the distance \( d \) from the critical point.

\[
Exposure_{\text{circle}} = CDFC(d, r)
\]

\[
Exposure_{\text{ring}} = CDFC(d, r_1) - CDFC(d, r_2)
\]
Non-Rectangular Features
- Exposure Estimation

**Direct Method**

- **Right triangle**
  Exposure contribution from a right triangle is derived from the CDFT table.

- **CDFT table**
  \( CDFT(x,y,w,h) \): exposure contribution from a right triangle whose right-angle vertex is at \((x,y)\) and width and height are \(w\) and \(h\), respectively.

\[
Exposure_{\text{triangle}} = CDFT(x, y, w, h)
\]
Non-Rectangular Features
- Exposure Estimation

**Slicing Method**

- Any (non-rectangular) correction shape may be decomposed into thin slices (exposure shapes) such that each slice is a rectangle.

- Then, the CDF table can be used to derive exposure contribution from each slice.
Non-Rectangular Features
- Exposure Estimation

**Hybrid Method**

- A correction shape which is not a basic shape may be decomposed into a set of exposure shapes of rectangles and right triangles.

- In order to minimize the number of exposure shapes, a portion of correction shape may be represented by a rectangle and negative right triangles.
Non-Rectangular Features
- Exposure Estimation

Coordinate Transformation

- A correction shape of rotated rectangle may be generated from a slanted bus line, a polygon, etc.

- The local coordinates \((x,y)\) centered at the critical point may be rotated such that the rectangle is not slanted (i.e., horizontally or vertically oriented) in the new coordinates \((x',y')\).

- Then, the CDF table may be used for exposure estimation.
Summary

• Hierarchical & look-up table: *fast, accurate, flexible*

• Shape & dose modifications, heterogeneous substrates, grayscale lithography, Non-rectangular primitives, etc.

• Further developments