Directed Self-Assembly of Block Copolymers
an other way to think lithography

R.Tiron et al.

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Outline

- Lithography: top-down or bottom-up
- CH shrink process implementation
- Perspectives
  - High resolution materials
  - Contact multiplication
- Summary
Optical lithography is a top-down approach

Photolithography is a process used in microfabrication to pattern parts of a thin film. It uses light to transfer a geometric pattern from a photomask to a light-sensitive chemical "photoresist" (resist) on the substrate. (wikipedia)
The big Jump from 193 nm to 13.5 nm

A real big jump is needed to achieve higher resolution
Self-assembly is a type of process in which a disordered system of pre-existing components forms an organized structure or pattern as a consequence of specific, local interactions among the components themselves, without external direction. (wikipedia)
Self-assembly everywhere in the nature
Phase separation governing self-assembly

Water-oil mixture

Block copolymers (BCP)

Self assembly based on phase separation: diff. morphologies accessible
Block copolymers: definitions

Different morphologies function of molecular fractions $f_A$ & $f_B$

- Morphology $\leftrightarrow$ concentration of each phase
- Pitch = period of the polymer = length of the chain
  - 1 polymer $\leftrightarrow$ 1 CD $\leftrightarrow$ 1 pitch ($L_0$)
- For constant morphology CD/pitch = ct

$\chi N$ large $\Rightarrow$ strong degree of phase separation

\[ L_0 \propto aN^\delta \chi_{AB}^{1/6} \]

\[ a = \left[ f_A a_A^2 + (1 - f_A) a_B^2 \right]^{1/2} \]

\[ \chi = c_1 + \frac{c_2}{T} \]

- $L_0$ : characteristic domain length scale
- $a$ : statistical segment length
- $N$ : number of chain segment
- $\chi$ : Flory Huggins parameter
- $\delta = 2/3$ in a strong segregation range
- $f$ : molecular fraction
- $T$ : temperature
- $c_1, c_2$ : constants
Block copolymers: orientation control

Domains orientation controlled by surface properties:
- Mandatory for lithographic applications
- Modified by chemical treatment, exposure, statistic block copolymers

X. Chevalier, R. Tiron et al., Proc of SPIE 2011, 7970
Pattern placement

Graphoepitaxy

Chemical epitaxy

- Solvent developed resist
- Hardened positive resist
- DSA + solvent developed resist
- DSA+ hardened positive resist

Cheng et al, ACS Nano, VOL. 4, NO. 8, 4815–4823, 2010, IBM Almaden Research Center

- Liu et al, JVST B. 28 (6), 2010, Univ. of Wisconsin
Directed Self Assembly for Microelectronics

Block copolymers self assembly capabilities
- Very high resolution
- Low intrinsic Line Edge Roughness
- Easy process
- Low cost

C-MOS Lithography constraints
- Control the domain orientations (1D - 2D)
- Alignment control with respect to a preview level
- Integration capabilities
- Low defectivity
- Respect of design rules
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How to go from R&D to industrial?

A production-oriented consortium

DSA Materials

Industrial scalability

Pre-industrial reactor

Lab. scale

Integration

300 mm INTEGRATION
- Defectivity
- Design compatibility

Process development

First 300 mm demonstration
- Process development
- Etch, Strip, …

Samples:
- Material compatibility
- Material properties

Process capability
- Throughput
- Patterning capability

Scale-up material qualification

Maturity III

Maturity II

Maturity I

Industrialization


**DSA program in LETI**

- **Push material platforms to maturity**
  - From lab scale to industry
  - Evaluate advanced copolymer platform

- **Develop 300mm patterning solutions**
  - Certify material compatibility with clean room standard
  - Screen DSA material performances
  - Verify transfer capabilities

- **Scale-up DSA processes to production level**
  - Compatibility with design rules
  - Respect of ITRS standard: defectivity, throughput...
DSA 300 mm process implementation

- No metallic contamination in polymers
- POR using cylindrical BCPs PS-\textit{b}-PMMA from Arkema
- Spin casting solvent: PGMEA
- Brush bake: 250C / 2min
- Non grafted brush removal: using PGMEA
- DSA bake: 250C / 2min
- PMMA remove wet and/or dry processes
- Two DSA dedicated tracks in Leti: SOKUDO DUO and TEL LITHIUS

“Pattern density multiplication by direct self-assembly of BCP: towards 300mm CMOS requirements” R. Tiron et al., SPIE2012
PMMA removal: wet treatment

- Only wet: missing contacts
- Need to depolymerize PMMA before wetting by different exposure treatments (ebeam, 193nm, implantation, etc)
DSA LETI’s 300 mm pilot line

193nm or e-beam litho pattern

BCP self-assembly

BCP pattern transfer

CD ~ 120nm

CD ~ 15nm

CD ~ 15nm

DSA Process of reference (lithographie and etch) available on 300 mm pilot line in Leti

M. Argoud et al. Proc of SPIE 2014 9049-81
Defectivity and CDU

POR on SOKUDO DUO Track using C35 from Arkema

Low defectivity

- 26796 measured points
- 0 missing contacts
- 100% hole open yield

Good CD control after DSA

\[
\begin{align*}
CD_{BCP} &= 25.5 \text{ nm} \\
3\sigma_{(CDU \text{ wafer})} &= 1.2 \text{ nm} \\
3\sigma_{(\text{local } CDU)} &= 1.09 \text{ nm} \\
(CD_{guide} = 55.2\text{nm} / 3\sigma = 4.3\text{nm})
\end{align*}
\]

Defectivity by CD-SEM image analysis:
- 154 contacts/field
- 3 images/chip
- 58 chips/wafer

Arkema first generation PS-b-PMMA materials (L0 = 35nm) deliver good performances on 300 mm pilot line (SOKUDO track)
BCP etching optimization

PS-PMMA transfer in typical 193 hard-mask is demonstrated
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Work axis on materials

PS-PMMA material (BCP and brush)
- Extendibility (determine high and low resolution limit)
- Material maturity ($35\text{nm} < L_0 < 46\text{nm}$)
  - Batch to batch repeatability
  - Contamination control
  - Life time
  - Evaluate the impact of physical-chemical polymer properties on patterning process window

High $\chi$ materials
- Identification of chemical platform
- Achieve Maturity 1 on Q4-2013

G.Fleury et al., Proc of SPIE 2014 9049-77
Broad range of PS-b-PMMA

$L_0 = 22 \text{ nm}$

$L_0 = 38 \text{ nm}$

$L_0 = 51 \text{ nm}$

$L_0 = 28 \text{ nm}$

$L_0 = 38 \text{ nm}$

$L_0 > 60 \text{ nm}$

Customizable PS-$b$-PMMA polymers with various pitch demonstrated

X. Chevalier et al, SPIE 2013 8680-5
Contact shrink: good test case to improve materials and processes
To implement DSA (ex. cuts), need to combine resolution and density

Complementary Lithography - View 2012

193i Gratings provide Critical EPE Control, NGL Enable Critical Masks Reduction

Gridded Layouts –
193i + Pitch Division + EUV Cuts with HVM EUV

Gridded Layouts –
193i + Pitch Division + EBDW Cuts with HVM EBDW

Gridded Layouts –
193i + Pitch Division + DSA Cuts with HVM DSA

Yan Borodovsky, Leti Innovation Days, June 26th 2013, Grenoble, France
Contact doubling

- Contact doubling demonstrated with DSA
- Pitch sizing possible with contact doubling approach

A.Gharbi et al. Proc of SPIE 2014 9049-58

Guiding template

BCP DSA

BCP etching

Cylindrical BCP (L0= 38nm) in guiding templates elliptical “eggs box”
What’s next: Exotic configurations

Complex structures available for contact multiplication by DSA to address design rules (hexagonal symmetry may be broken)
Pattern prediction and simulation

Complex structures available for contact multiplication by DSA to address design rules
DSA physical modeling

Model based on spinodal decomposition and the Cahn-Hilliard equation

Guidings

Simulation

Experimental

Physical modeling will be used to calibrate a compact model

Cortosy to S.Moulis, J.Belledent
Predicting polymer structures: compact model

- Design
- Calculated CH placement

Simulation contour

Contour variation w.r.t. dose, focus and mask CD error variations

Experimental validation

Pattern multiplication: process available and simulation tools under development
Summary

● DSA is a complementary lithography technique
  - In a first step by using PS-b-PMMA like materials (lowest CD after etching 10nm); In a second step by using high $\chi$ materials

● A credible alternative for contact and via patterning
  - CDU is improved by using DSA $3\sigma < 2$nm
  - Defectivity 5 defects per wafer (99.97% of good contacts): need to move to automatic measurements
  - Etching capabilities demonstrated
  - Metrology DSA is in film order: need to implement hybrid approach

● What’s next: 2D structures
  - Physical and compact models have to be implemented in order to predict order
Next generation lithography: Probably both together

**Top-down:** Externally controlled tools are used to cut materials into the desired shape and order. (ex. conventional lithography)

**Bottom-up:** Assemble nano objects out of smaller units (ex. Block Copolymers)

These terms were first applied to the field of nanotechnology by the Foresight Institute in 1989 Probably both together

<table>
<thead>
<tr>
<th>LITHOGRAPHY REQUIREMENTS</th>
<th>TOP-DOWN</th>
<th>BOTTOM-UP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RESOLUTION:</strong> minimum linewidth or space that may be printed</td>
<td>—</td>
<td>+</td>
</tr>
<tr>
<td><strong>REGISTRATION:</strong> degree to which the pattern can be aligned to previously printed features</td>
<td>+</td>
<td>—</td>
</tr>
<tr>
<td><strong>REPRODUCIBILITY:</strong> Ability to produce the same feature size across an entire wafer</td>
<td>+</td>
<td>—</td>
</tr>
<tr>
<td><strong>THROUGHPUT:</strong> The time to complete a print</td>
<td>+</td>
<td>+</td>
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</tbody>
</table>
All this is possible thanks to:


PhD and internship position available in our team
To join us please contact me raluca.tiron@cea.fr

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