Evaluation of Technology Options by Lithography Simulation

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Semicon Europe, Dresden, October 12, 2011
• Introduction:
  Resolution limits of optical and EUV lithography

• ArF immersion/double patterning:
  process interactions in double patterning

• EUV lithography:
  impact of multilayer mask defects

• Lithography beyond semiconductor manufacturing:
  source & mask optimization for mask aligners

• Conclusions and Outlook
**Introduction: Resolution Limit**

**ArF Immersion Lithography: Single Patterning**

- $k_1 > 0.7$: “perfect” imaging
- $0.25 < k_1 \leq 0.7$: optical proximity effects: OPC/SMO required
- $k_1 = 0.25$: theoretical limit of half pitch (HP) for single exposure

$CD = k_1 \frac{\lambda}{NA}$

$\lambda=193\text{nm}, NA=1.35$, circular illum. $\sigma=0.9$
**Introduction: Resolution Limit**

ArF Immersion Lithography: Single & Double Patterning

**single patterning exposure**

- $k_1 \leq 0.25$ impossible

**double patterning exposure 1**

- $k_1 = 0.14$ possible → 20nm features
- requires extensive SMO, two masks and additional process steps
- manufacturable but (very) expensive

**double patterning exposure 2**
**EUV Lithography: Single Patterning**

- $\lambda = 13.5\text{nm}$, $\text{NA} = 0.32$, circular illum. $\sigma = 0.7$

- $k_1 > 0.75$, 32nm: no OPC required
- $k_1 > 0.45$, 19nm: doable with standard OPC
- $k_1 \leq 0.24$, 17nm: requires more aggressive OPC/SMO
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Process Interactions in Double Patterning

Crossed Lines: Contact Formation Using Litho-Curing-Litho-Etch

H. Nakamura et al. J. Micro/Nanolith.MEMS MOEMS, 2008, 7, 043001

mask:
AttPSM with 45nm lines/spaces

stepper:
ArF, NA=1.25, y-pol./TE,
dipole illumination:
σ=0.76/0.89,
opening angle 35°

resist:
DOW electronic materials, thickness 100nm

wafer:
Bilayer BARC on Si

spin-on resist 1
lithography 1
cure and spin-on resist 2
lithography 2
dose = 21.3mJ/cm2

SEM pictures with courtesy of Dow Electronic Materials

43.98nm / 43.12nm
Impact of incomplete Cure of Litho 1 Resist

Curing is modeled by an increase of the activation energy of the cured resist $E_{aF}$ compared to that of the litho 2 resist $E_{a2}$.

Imperfect curing causes barrel shaped contact holes.
Impact of Wafer Topography during Litho 2 Exposure

- Effect is linear in $\Delta n$
- Material specifications have to be defined for critical pitches
- Consider critical pitch in the design split!

**Process Interactions in Double Patterning**

**Impact of Wafer Topography during Litho 2 Exposure**

- litho 1: 45nm lines; variable pitch
- litho 2: 45nm lines; 90nm pitch

$\Delta n = 0.03$ (difference between refractive indices of cured resist and litho 2 resist)
Acid Diffusion between Different resist Materials

- Acid diffusion length in cured resist: $d_{A1}$
- Acid diffusion length in litho 2 resist: $d_{A2}$

- $d_{A1/2} = 10/4 \text{ nm}$
- $d_{A1/2} = 10/12 \text{ nm}$
- $d_{A1/2} = 10/20 \text{ nm}$

- Acid depletion close to litho1 line due to diffusion from resist 2 to cured resist 1, thus becoming unavailable for deprotection reaction.

- Resist interaction effects explain footing which was experimentally observed in some resist formulations.

SEM pictures with courtesy of Dow Electronic Materials.

Lithography Simulation

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* There are strong activities on EUV source modeling outside the “standard” lithography simulation community
Impact of Multilayer Mask Defects

40nm Dense Lines Printing without/with Defect

**mask**

**image**

**resist**

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**no defect**

\[ \lambda = 13.5\text{nm}, \quad \text{NA} = 0.25, \quad \text{circular illum.} \quad \sigma = 0.5 \]

**calibrated resist model**

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**defect**

- \( w_{\text{top}} = 80\text{nm} \)
- \( h_{\text{top}} = 2\text{nm} \)
- \( w_{\text{bot}} = 50\text{nm} \)
- \( h_{\text{bot}} = 50\text{nm} \)
Impact of Multilayer Mask Defects

Description of Defects

- bump defect
- pit defect

(2D) Gaussian deformation at top/bottom:

\[ h_{\text{top/bot}} \] – defect height
\[ w_{\text{top/bot}} \] – defect size (FWHM)

- introduced during mask fabrication
- shape depends on multilayer deposition process
- difficult to find and to repair
Impact of Multilayer Mask Defects

Defect Images without absorber versus Defocus

- bump defect
  - \(h_{\text{top}} = 2\,\text{nm}\)
  - \(w_{\text{top}} = 75\,\text{nm}\)
  - \(h_{\text{bot}} = 30\,\text{nm}\)
  - \(w_{\text{top}} = 30\,\text{nm}\)

- pit defect
  - \(h_{\text{top}} = -2\,\text{nm}\)
  - \(w_{\text{top}} = 100\,\text{nm}\)
  - \(h_{\text{bot}} = -2\,\text{nm}\)
  - \(w_{\text{top}} = 100\,\text{nm}\)

- defects cause intensity loss in defect area
- asymmetric printing through focus
- bumps and pits print most severe in opposite focus directions
Impact of Multilayer Mask Defects

Comparison with Experiment

pit

bump

defocus

SEMs from: R. Jockheere, IMEC
Impact of Multilayer Mask Defects

Modeling of Present Repair Strategy

Mask layout  Aerial image  Resist profile

- Good repair at best focus
- How about through-focus?

Mask: 40nm dense L/S
Optics: NA=0.25, λ=13.6nm, σ=0.5
Resist: calibrated to IMEC data
Defect: top 2/80nm, bottom: 10/10nm
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## Lithography beyond Semiconductor Manufacturing

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<td>Diversity of Techniques</td>
<td>Comparison of projection and proximity printing, interference lithography, direct optical and e-beam write, near field methods, …</td>
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<td>Resolution and other Limitations of various techniques</td>
<td>Source &amp; mask optimization for mask aligners, exploration of Talbot imaging, various near field methods and optical nonlinearities (two-photon processes, stimulated/depleted polymerization)</td>
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<tr>
<td>Diversity of applications, materials, and special Requirements</td>
<td>Modeling of thick resist effects, gray tone techniques, coupling between lithography and optical device simulation for waveguide structures and nano-photonics</td>
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Source & Mask Optimization for Mask Aligners

Customized Illumination Geometry: SUSS Microoptics Exposure Optics

Aligner pictures and SEMs from: R. Völkel, SUSS MicroOptics
Conclusions and Outlook

Full physical lithography simulation can be used to:

• Compare technology options
• Investigate impacts of device/process parameters
• Optimize existing and future processes
• Explore resolution limits of emerging new techniques

Some future trends:

• Diversity of technology options, related physical/chemical effects and application specific process criteria requires more flexible and open simulation infrastructure
• Combination of simulation and metrology will enable new possibilities for process control
• Combination of predictive simulation and advanced optimization techniques helps to push the limits of micro- and nanopatterning techniques
Acknowledgements

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