Lawrence Berkeley National Laboratory
Recent Work

Title
Printing EUV Phase-shift Masks using the 0.3NA Berkeley Micro-exposure Tool

Permalink
https://escholarship.org/uc/item/4zv2405r

Authors
Fontaine, Bruno La
Pawloski, Adam R.
Wood, Obert R.
et al.

Publication Date
2005-03-25
Printing EUV Phase-Shift Masks using the 0.3NA Berkeley MET

4th International EUVL Symposium - San Diego, November 2005

Bruno La Fontaine, Adam R. Pawloski, Obert R. Wood II, Harry Levinson
Advanced Micro Devices, One AMD Place, Sunnyvale CA 94088-3453, USA
Paul Denham, Eric Gullikson, Brian Hoef
Lawrence Berkeley National Laboratory, Berkeley CA, USA
Patrick Naulleau
College of Nanoscale Science and Engineering, University at Albany, Albany, NY
Christian Holfeld, Christian Chovino
Advanced Mask Technology Center, Dresden, Germany
Florian Letzkus
Institute for Microelectronics, Stuttgart, Germany
CPL-like phase-shift masks for EUVL

- We have demonstrated the printing of EUV phase-shift masks based on direct etching of the multilayer reflector.
- This is illustrated by phase-edge printing in resist of etched features on the mask.
Outline of the presentation

• Concept and design of EUV phase-shift masks
• The fabrication of phase-shift masks
• First printing results and simulations
• Spectral response
• Early results from second mask
• Future work
EUV phase-shift mask concept

- The EUV PSM concept that we are evaluating is based on etched multilayer techniques
- EUV PSMs are needed for focus and aberration monitoring
- EUV PSMs can also provide high contrast aerial images at small CD for resist testing

The etch depth controls the phase angle

The number of remaining bilayers controls the attenuation relative to full stack reflectance

The total number of bilayers controls the overall stack reflectance

Any type of PSM can be fabricated this way: CPL, att-PSM, alt-PSM
Types of EUV Phase-shift masks

- CPL-like (PSM1 & PSM3)
  - ~ 100 nm etch for 180°
  - >40 bilayer provides almost full reflectance

- Att-PSM (PSM2)
  - ~ 300 nm etch for 180°
  - A few bilayers left to provide ~10% of top layer reflectance

- Alt-PSM (not yet fabricated)
  - ~ 100 nm etch for 180°
  - Absorber or complete etch can provide desired contrast
EUV PSM design

- Index of refraction of multilayer is very close to that of vacuum
  \[ \frac{2\Delta n t}{\lambda \cos \theta} = \frac{\Delta \phi}{2\pi} \quad \text{with} \quad \Delta n \sim 0.03 \quad \Rightarrow \quad \frac{t}{\Delta \phi} \sim 0.6 \text{nm/°} \]

- π phase shift corresponds to ~ 110 nm etch depth
The fabrication of EUV Phase-shift masks

- Description of process flow (AMTC/IMS-Chips)
First etched-multilayer EUV PSM
PSM1 is a ‘CPL-like’ phase-shift mask

Final Mask (Post-hardmask Strip)
Sample features on PSM1 mask

- Etch depth of 81 nm with good uniformity across the central imaging area
First print with mask PSM1

- Phase edges of this ‘CPL’ mask clearly print
- This is the first print recorded using an EUV phase-shifting mask patterned by partially etching the multilayer reflector film
  - \(\lambda=13.5\) nm, monopole illumination, resist: MET 1K on BARC
  - Programmed 80-nm lines & spaces
Through focus behavior of PSM1 print

- Tone reversal observed (characteristic of phase objects)
  - 100 nm focus steps at constant dose
Comparing PSM1 results to simulations

- Fair qualitative agreement:
  - Trend showing frequency doubling and tone reversal through focus is reproduced in the simulations

**PSM1 prints**

- f=-400nm
- f=-300nm
- f=-200nm
- f=-100nm
- f=0nm
- f=100nm
- f=200nm
- f=300nm

**π-shift mask simulations**

- f=-500nm
- f=-200nm
- f=0nm
- f=200nm
- f=500nm
Comparing PSM1 results to simulations

- Simulations using a shallower etch depth are in better agreement with the experimental results.
Tuning the spectrum for optimum phase shifting

- Etch depth = 100nm
- Aerial images through focus (+/- 200 mm)
- Results appear best at ~ 13.4 nm
Simulated at-wavelength reflectance and diffraction

- The simulated response of an etched-multilayer PSM indicates that the 105nm etch depth should be optimized for 13.4 nm imaging.

![Graph showing fractional order strength vs wavelength for different etch depths and orders. The graph highlights the best 1st/0th order ratio at around 13.4 nm.]
At wavelength reflectivity measurements

- Measured spectral response of our masks indicates that both PSM1 and PSM3 were under etched
  - These experimental data show first order peaking at a wavelength shorter than 13.4 nm
  - This is consistent with the observed print results, which are the best at 13.3 nm for PSM3

- Notable improvement from PSM1 to PSM3
  - Etch depth of 80nm for PSM1 vs. 105nm for PSM3

Spectral Response of EUV-PSM1

Spectral Response of EUV-PSM3

best 1st/0th order ratio
Measured diffracted orders for PSM1 & PSM3

- Diffracted orders measured at 13.5 nm
  - Large contribution from zeroth order consistent with inadequate phase-shifting observed in printing experiments for PSM1
PSM3 diffracted orders through wavelength

- Diffracted orders measured at 13.25 nm, 13.3 nm, and 13.5 nm
  - Much better suppression of zeroth order at 13.3 nm
Overview of initial results with PSM3 at $\lambda=13.3$ nm

- Mask: PSM3 with etch depth=105nm
- Illumination: monopole
- Phase-edge printing with excellent resolution and LER

Phase-edge prints of 80nm lines
CD=38nm, LER=4nm

Phase-edge prints of 70nm lines
CD=38nm, LER=4.8nm

1:1 35nm lines
CD=36nm, LER=3.9nm
PSM3 mask printing results

- Second ‘CPL’ mask has 105 nm etch depth
- Prints also match $\pi$-phase-shift simulation better
- Images of programmed 1:1 80-nm lines through focus are shown below.

![Images of programmed 1:1 80-nm lines through focus](f=100nm, f=200nm, f=300nm, f=400nm, f=500nm)
Conclusions and Future Work

• Successful demonstration of the use of EUV phase-shift masks for printing fine resist features

• Phase-shift prints appear to be limited by resist resolution
  – Observed performance is very similar to that of dark-field binary mask, even though the PSM is completely bright

• We are planning to build and test an att-PSM mask next
  – A PGFM mask for focus monitoring will also be fabricated in the future

• Simulations
  – Good qualitative agreement with experiments
  – What is the influence of sidewall angle on the performance of PSMs?
  – What is the effect of biasing or duty cycle?

• Assess degradation over time
  – Early measurements do not reveal any significant reflectance loss
  – Regular measurements of PSM1 and PSM3 have been planned at LBL (ALS)