NGL 2005, 7-8, July, 2005 at NATIONAL MUSEUM OF EMERGING SCIENCE AND INNOVATION, Tokyo, Japan

Advanced 0.3-NA EUV lithography capabilities at the ALS

Patrick Naulleau[1], Erik Anderson[2], Kim Dean[3], Paul Denham[2], Kenneth A. Goldberg[2], Brian Hoef[2], Keith Jackson[2]

[1]CNSE, University at Albany, Albany, NY 12203
[2]CXRO, Lawrence Berkeley National Lab., Berkeley, CA 94720
[3]SEMATECH, Austin, TX 78741

PNaulleau@uamail.albany.edu

1. Introduction

For volume nanoelectronics production using Extreme ultraviolet (EUV) lithography [1] to become a reality around the year 2011, advanced EUV research tools are required today. Microfield exposure tools have played a vital role in the early development of EUV lithography [2-4] concentrating on numerical apertures (NA) of 0.2 and smaller. Expected to enter production at the 32-nm node with NAs of 0.25, EUV can no longer rely on these early research tools to provide relevant learning. To overcome this problem, a new generation of microfield exposure tools, operating at an NA of 0.3 have been developed [5-8]. Like their predecessors, these tools trade off field size and speed for greatly reduced complexity. One of these tools is implemented at Lawrence Berkeley National Laboratory's Advanced Light Source synchrotron radiation facility. This tool gets around the problem of the intrinsically high coherence of the synchrotron source [9,10] by using an active illuminator scheme [11]. Here we describe recent printing results obtained from the Berkeley EUV exposure tool. Limited by the availability of ultra-high resolution chemically amplified resists, present resolution limits are approximately 32 nm for equal lines and spaces and 27 nm for semi-isolated lines.

2. Predicted resolution limit

The Berkeley exposure tool utilizes SEMATECH's 5×-reduction, 0.3-NA Micro-Exposure Tool (MET) optic [12,13]. The MET optic has a well-corrected field of view of 1×3 mm at the reticle plane (200×600 µm at the wafer plane). The CAD model shown in Fig. 1 depicts the major components of the exposure station as well as the EUV beam path (the system is described in detail in Ref. 5). With a NA of 0.3, the MET optic has a Rayleigh resolution

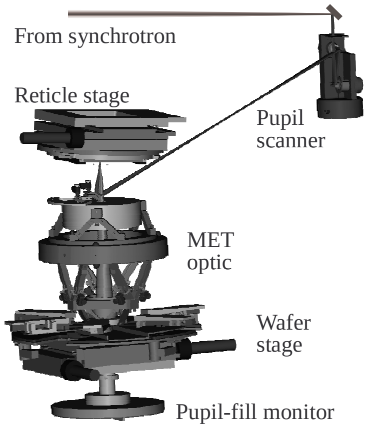

Fig. 1. CAD model of the Berkeley MET exposure tool.

(k_1 factor = 0.61) of 27 nm. As shown in Fig. 2, using the programmable coherence illuminator to generate resolution enhancing pupil fills, however, enables the k_1 factor to be pushed significantly below the Rayleigh limit.

3. Resist characterization

Since printing operations began in February 2004, more than 140 resist and 12 masks have been tested by users from 15 different organizations. The system has already played a crucial role in enabling the development of high-resolution chemically amplified resists. In the past, the mainstay resist of EUV research in the US was Rohm and Haas *EUV-2D*, however, this resist has now been shown [6] to have a resolution limit of approximately 45 nm, in good agreement with previous predictions [15]. Using the Berkeley tool, superior resist formulations were quickly identified. Figure 3 shows printing results in Rohm and Haas *MET-1K* resist, demonstrating resolution down to 35 nm.

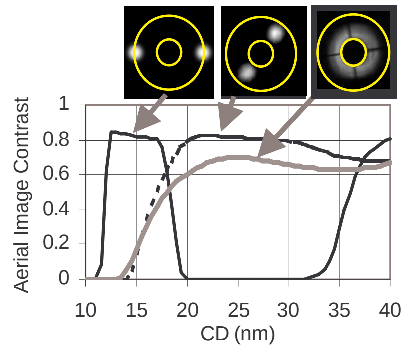

Fig. 2. Modeling of the aerial image contrast transfer function for three different pupil fills.

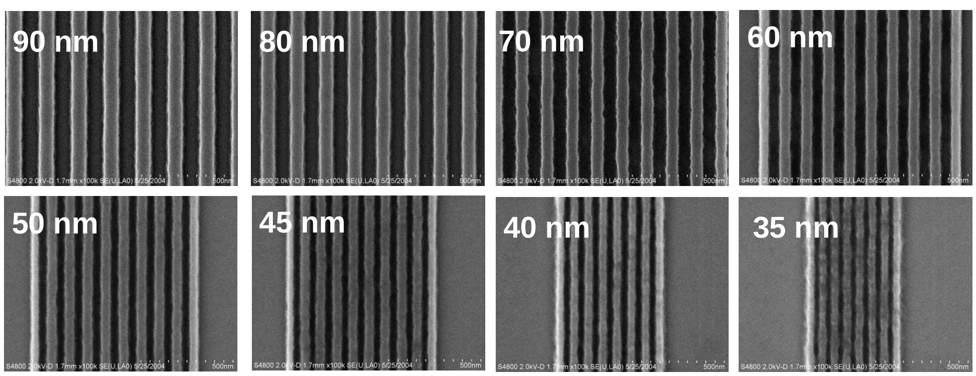

Fig. 3. Equal lines and spaces printed in 125-nm-thick layer of Rohm and Haas *MET-1K* resist under annular (0.3-0.7) illumination.

Of the more than 140 resists tested in the Berkeley system, there have been two groups of clear stand-outs: one of these groups is *MET-1K* and its variants and the other group is experimental *KRS* resists provided by IBM [16]. Figure 4 shows a series of equal line space images ranging from 45 to 30 nm printed in experimental *KRS* resist under annular illumination $0.3 < \sigma < 0.7$. Going to monopole illumination optimized for larger pitches, Fig. 5 shows 35-nm equal lines and spaces as well as semi-isolate 28-nm features.

4. Acknowledgements

Special thanks are due to Robert Brainard and Thomas Koehler of Rohm and Haas as well as

Greg Wallraff and Carl Larson of IBM for providing resist materials and expert processing support. We also acknowledge the entire CXRO staff for enabling this research. This research was performed at Lawrence Berkeley National Laboratory and supported by International Sematech. Lawrence Berkeley National Laboratory is operated under the auspices of the Director, Office of Science, Office of Basic Energy Science, of the US Department of Energy.

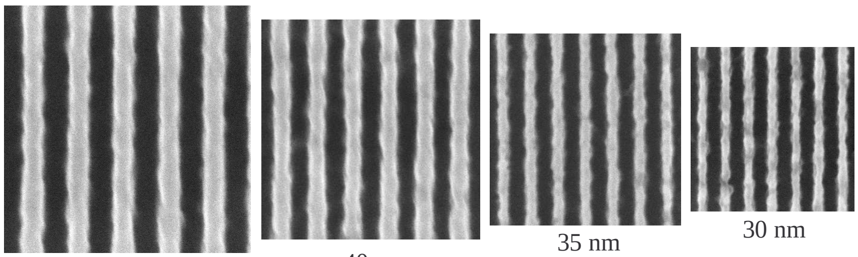

Fig. 4. Equal line space images ranging from 45 to 30 nm printed in experimental *KRS* resist under annular illumination 0.3 < σ < 0.7.

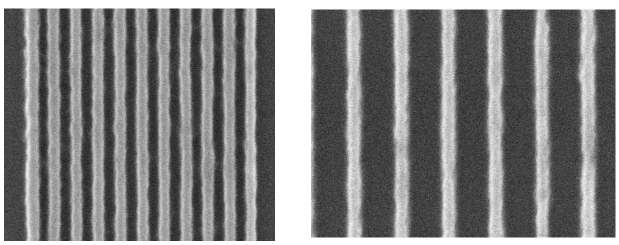

Fig. 5. Images recorded in *KRS* resist under monopole illumination. (a) 35-nm lines and spaces and (b) coded 27.5-nm lines 110-nm pitch, actual printed size in resist is 28.3-nm.

5. References

1. R. Stulen and D. Sweeney, "Extreme ultraviolet lithography," IEEE J. Quantum Electron. **35**, 694-699 (1999).
2. J. Goldsmith, K. Berger, D. Bozman, G. Cardinale, D. Folk, C. Henderson, D. O'Connell, A. Ray-Chaudhuri, K Stewart, D. Tichenor, H. Chapman, R. Gaughan, R. Hudyma, C. Montcalm, E. Spiller, J. Taylor, J. Williams, K. Goldberg, E. Gullikson, P. Naulleau, J. Cobb, "Sub-100-nm lithographic imaging with an EUV 10´ microstepper," Proc. SPIE **3676**, 264-271 (1999).
3. K. Hamamoto, T. Watanabe, H. Tsubakino, H. Kinoshita, T. Shoki, M. Hosoya, "Fine pattern replication by EUV lithography," Journal of Photopolymer Science & Technology **14**, 567-572 (2001).
4. P. Naulleau, K. Goldberg, E. Anderson, D. Attwood, P. Batson, J. Bokor, P. Denham, E. Gullikson, B. Harteneck, B. Hoef, K. Jackson, D. Olynick, S. Rekawa, F. Salmassi, K. Blaedel, H. Chapman, L. Hale, P. Mirkarimi, R. Soufli, E. Spiller, D. Sweeney, J. Taylor, C. Walton, D. O'Connell, R. Stulen, D. Tichenor, C. Gwyn, P. Yan and G. Zhang, "Sub-70-nm EUV Lithography at the Advanced Light Source Static Microfield Exposure Station Using the ETS Set-2 Optic," J. Vac. Sci. & Technol. B **20**, 2829-2833 (2002).

5. P. Naulleau, K. Goldberg, E. Anderson, K. Bradley, R. Delano, P. Denham, R. Gunion, B. Harteneck, B. Hoef, H. Huang, K. Jackson, M. Jones, D. Kemp, J. Liddle, R. Oort, A. Rawlins, S. Rekawa, F. Salmassi, R. Tackaberry, C. Chung, L. Hale, D. Phillion, G. Sommargren, H. Taylor, "Status of EUV micro-exposure capabilities at the ALS using the 0.3-NA MET optic," Proc. SPIE **5374**, 881-891 (2004).
6. P. Naulleau, K. Goldberg, J. Cain, E. Anderson, P. Denham, K. Jackson, S. Rekawa, F. Salmassi, G. Zhang, "EUV Microexposures at the ALS using the 0.3-NA MET Optic," J. Vac. Sci. & Technol. B **22**, 2962-2965 (2004).
7. A. Brunton, J. S. Cashmore, P. Elbourn, G. Elliner, M. C. Gower, P. Gruenewald, M. Harman, S. Hough, N. McEntee, S. Mundair, D. Rees, P. Richards, V. Truffert, I. Wallhead, M. D. Whitfield, "High-resolution EUV imaging tools for resist exposure and aerial image monitoring," Proc. SPIE **5751**, 78-89 (2005).
8. H. Oizumi, Y. Tanaka, I. Nishiyama, H. Kondo, K. Murakami, "Lithographic performance of high-numerical-aperture (NA=0.3) EUV small-field exposure tool (HINA)," Proc. SPIE **5751**, 102-109 (2005).
9. D. Attwood, G. Sommargren, R. Beguiristain, K. Nguyen, J. Bokor, N. Ceglio, K. Jackson, M. Koike, and J. Underwood, "Undulator radiation for at-wavelength interferometry of optics for extreme-ultraviolet lithography," Appl. Opt. **32**, 7022-7031 (1993).
10. C. Chang, P. Naulleau, E. Anderson, and D. Attwood, "Spatial coherence characterization of undulator radiation," Opt. Comm. **182**, 24-34 (2000).
11. P. Naulleau, K. Goldberg, P. Batson, J. Bokor, P. Denham, and S. Rekawa, "A Fourier-synthesis custom-coherence illuminator for EUV microfield lithography," Appl. Opt. **42**, 820-826 (2003).
12. J. Taylor, D. Sweeney, R. Hudyma, L. Hale, T. Decker, G. Kubiak, W. Sweatt, N. Wester, "EUV Microexposure Tool (MET) for near-term development using a high NA projection system," 2nd International EUVL Workshop October 19-20, 2000 (http://www.sematech.org/resources/litho/meetings/euvl/20001019/707_SYS07_taylor.pdf)
13. R. Hudyma, J. Taylor, D. Sweeney, L. Hale, W. Sweatt, N. Wester, "E-D characteristics and aberration sensitivity of the Microexposure Tool (MET)," 2nd International EUVL Workshop October 19-20, 2000 (http://www.sematech.org/resources/litho/meetings/euvl/20001019/hudyma.pdf).
14. J. Cain, P. Naulleau, C. Spanos, "Lithographic measurement of EUV flare in the 0.3-NA MET optic," Proc. SPIE **5751**, 301-311 (2005).
15. P. Naulleau, "Verification of point-spread function based modeling of an EUV photoresist," Appl. Opt. **43**, 788-792 (2004).
16. G. M. Wallraff, D. R. Medeiros, M. Sanchez, K. Petrillo, W. Huang, C. Rettner, B. Davis, C. E. Larson, L. Sundberg, P. J. Brock, W. D. Hinsberg, F. A. Houle, J. A. Hoffnagle, D. Goldfarb, K. Temple, S. Wind, and J. Bucchignano, "Sub-50 nm half-pitch imaging with a low activation energy chemically amplified photoresist," *J. Vac. Sci. Technol. B* **22**, 3479–3484 (2004).