Soft X-Ray Microscopy and EUV Lithography: An Update on Imaging at 20–40 nm Spatial Resolution

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Soft X-Ray Microscopy and EUV Lithography: An Update on Imaging at 20–40 nm Spatial Resolution

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Abstract. Major advances in both soft x-ray microscopy, at wavelengths from 0.6 to 4 nm, and EUV lithography, at wavelengths between 13 and 14 nm, are reviewed. In the XRL-2000 proceedings[1] we reported soft x-ray microscopy resolved to 25 nm, in static two-dimensional imaging, with applications to biology, magnetic materials, and various "wet" environmental samples. In this 2002 update we report significant extensions to three-dimensional tomographic imaging,[2] dynamical studies of magnetic[3] and electronic devices,[4] and static two-dimensional microscopy poised for extension to below 20 nm spatial resolution.[5] In the XRL-2000 proceedings we reported EUV lithographic imaging of 50 nm lines/100 nm spaces in static microfield (~100 μm) exposures. In this 2002 update we report scanned full-field (25 mm by 32 mm) images at better than 100 nm lines/100 nm spaces,[6] static microfield exposures down to 50 nm lines/50 nm spaces, and isolated lines to 39 nm wide at 0.1 NA.[7] With soon to be available 0.3 NA optics,[8] we expect to print isolated lines, in static micro exposures, at 16–20 nm width in 2003. These results will demonstrate EUV lithography's ability to meet not only the ITRS Roadmap[9] 45 nm node (26 nm isolated lines in resist) in 2007, but also the 32 nm node (18 nm isolated lines in resist) in 2009, both of which the semiconductor industry is now preparing for.[10]

1. SOFT X-RAY MICROSCOPY

High resolution soft x-ray microscopy is based on the use of Fresnel Zone plate lenses with narrow, accurately placed outer zones,[11] and a properly aligned and illuminated microscope. In the XRL-2000 proceedings we reported on state-of-the-art zone plates of 25 nm outer zone width (Δr), of 25 nm thick nickel zones (1:1 aspect ratio),[5] achieving a record 23 nm spatial resolution, albeit with modest diffraction efficiency. Using new nanofabrication techniques for both zone plate lenses and test patterns, soon to be reported results[12] will show clearly resolved images to 20 nm lines and spaces, with expectations to move below 20 nm in the coming months.

While pushing ahead with improved spatial resolution in two-dimensional soft x-ray imaging, great progress has also been made with three-dimensional (3D) microtomography of cryofixed biological materials[2,13] and, separately, two-dimensional (2D) dynamical studies for the physical sciences.[3,4] The soft x-ray microtomography

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2002 American Institute of Physics 0-7354-0096-2

technique was developed by the Göttingen group[14] in Germany, and has recently been extended to further applications in Berkeley.[2,13,15] Figure 1 illustrates the use of a rotating capillary tube, containing the sample under study, to affect micro-tomographical imaging in the soft x-ray microscope. To accommodate the need for greater working distance, increased depth of focus, and improved efficiency special zone plate lenses with somewhat larger onto zone width ($\Delta t = 40$ nm) and thickness are used, with a concomitant but modest loss of resolution. Figure 2 shows 2D slices from a full 3D tomographic image of a single cryofixed drosophila melanogaster cell. At the conference this was shown as a 3D rotating image of the cell.*

Dynamical studies using soft x-ray microscopy have also been introduced in the past year, to date for applications in the physical sciences. These studies include observations of magnetic materials switching, by in-plane applied magnetic fields at a

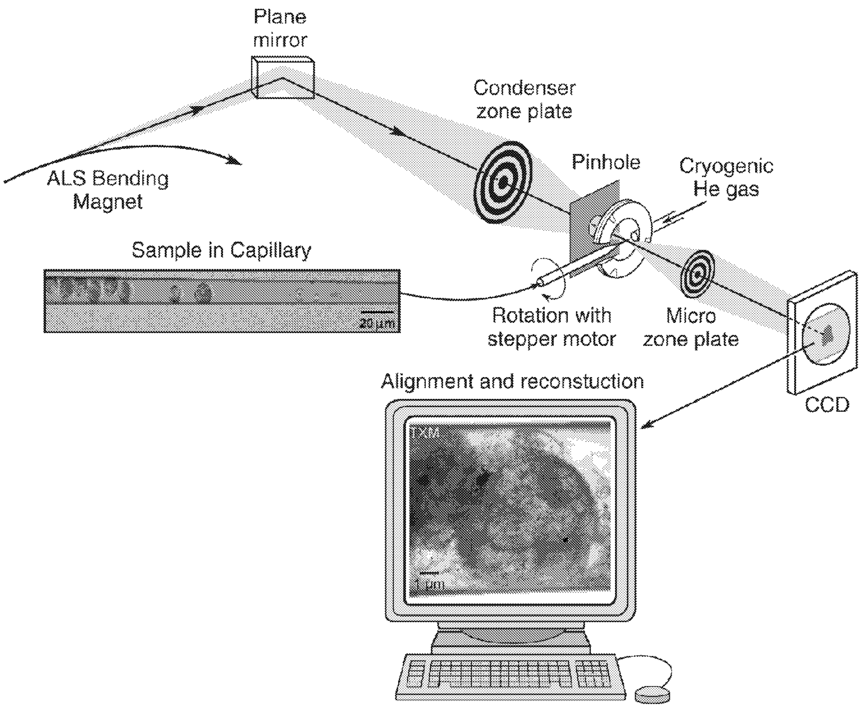

FIGURE 1. Soft x-ray tomography at high spatial resolution obtained with a rotating sample holder in the full field microscope at LBNL's Advanced Light Source. Rotating 3D images of the cell were shown at the conference. Courtesy of Dr. Gerd Schneider.[2]

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* Contact Dr. Gerd Schneider, Center for X-Ray Optics, Lawrence Berkeley National Laboratory (GRSchneider@lbl.gov) regarding the CD movie clip displaying the full tomographic data.

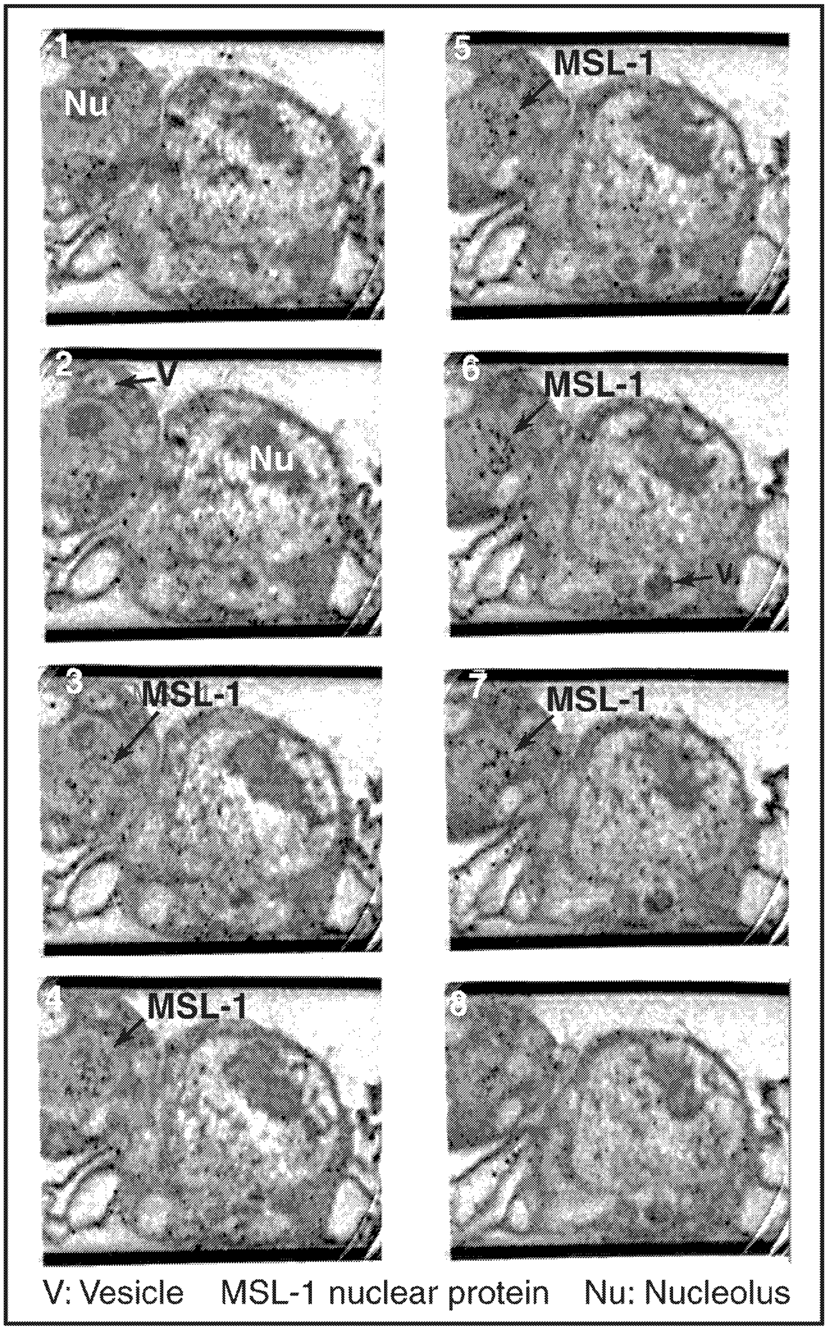

FIGURE 2. Eight transverse 2D slices through a 3D tomographic image of a single biological cell, obtained with cryofixation of the sample, and use of the microscope shown in Figure 1. Courtesy of Dr. Gerd Schneider.[2]

resolution sufficient to observe single magnetic grains.[3] Dynamic studies of void formation in high current density nanochip "vias" (layer to layer electrical interconnects) have also been conducted. These voids correspond to atomic transport driven by intense and continued electron bombardment within the narrow conduction pathway. Figure 3 shows a soft x-ray micrograph (1.8 keV, 0.6 nm wavelength) of a side thinned nanoelectronic shop where void formation and movement within a copper interconnect ("via") are studied. Movies of void formation and movement, obtained by sequential soft x-ray imaging,[4] were shown at the conference. Correlation with high electron energy TEM studies indicates that void formation tends to occur near grain

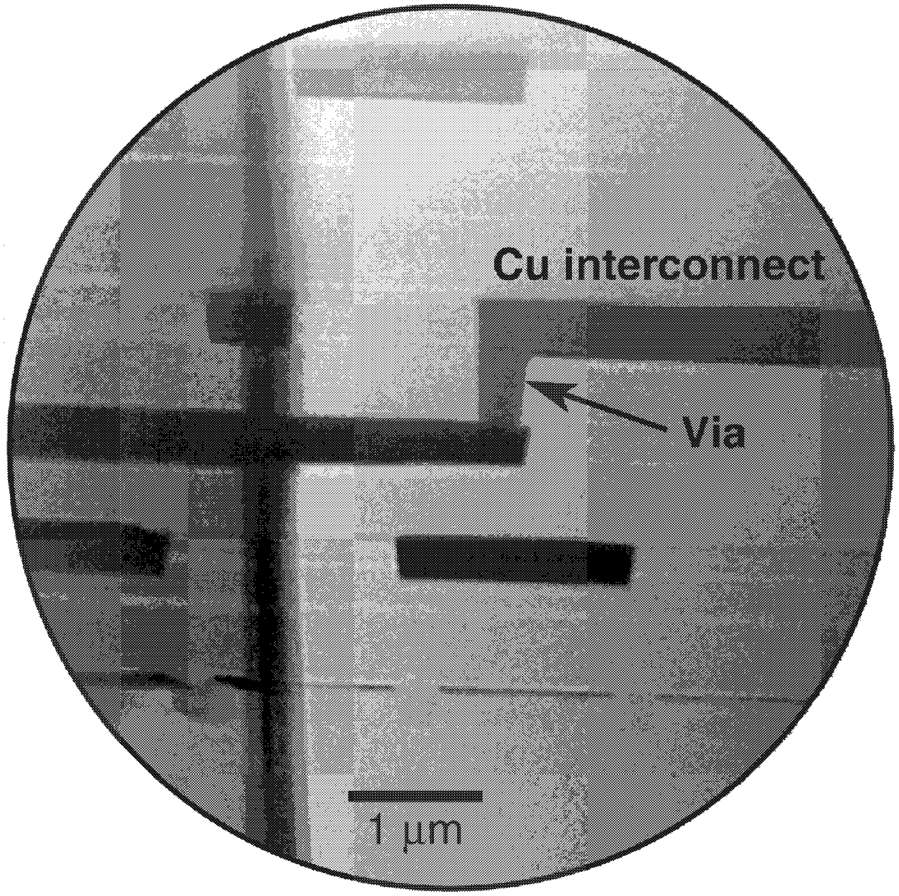

FIGURE 3. X-ray microscope image, obtained at 1.8 keV, looking through the vertical stack of interconnected layers of a computer chip. The layers of electronic patterns are interconnected by copper "vias." Density voids in the Cu appear due to electron bombardment at high current density. The growth and movement of voids within the Cu via, leading to catastrophic failure in some cases, is studied dynamically using sequential images. Movies of the void formation and movement where shown at the conference. Courtesy of Dr. Gerd Schneider.[4]

boundaries within the metallic material, with void migration along these boundaries toward the surface or materials interface, eventually leading to complete structural failure at sufficiently high current density and time duration.[4] For a summary of the most recent advances in high resolution soft x-ray microscopy, with broad applications to the physical and life sciences, see the proceedings of International X-Ray Microscopy Conference, XRM-2002.

2. EXTREME ULTRAVIOLET (EUV) LITHOGRAPHY

Lithography is the process of copying patterns, used currently with deep ultraviolet (DUV) lasers (KrF at 248 nm; Arf at 193 nm) and sophisticated multi-element (20 lenses) optical de-magnification cameras ("steppers") to print the most advanced computer chip patterns. A typical electronic device today (Pentium 4 by Intel, Athlon by AMD) consists of about twenty such overlaid and interconnected patterns, each up to 25 mm × 32 mm in size, containing a total of about fifty million transistors. For the recent (2001) "130 nm node" (half the period of the finest optical image of equal lines and spaces patterns), isolated lines of 90 nm width were printed in resist (narrowed by near-threshold resist processing) and further narrowed by materials processing to 65 nm during transfer of the pattern to a conducting material (the "metalization" step). Figure 4 shows a recently updated[9] table, the International Technology Roadmap for Semiconductors (ITRS, December 2001), giving the various nodes, half-pitch optical

First year of volume production	**2001**	2003* ~~**2004**~~	2005* ~~**2007**~~	2007* ~~**2010**~~	2009* ~~**2013**~~	2011* ~~**2016**~~
Technology Generation (Dense lines, printed in resist)	130 nm	90 nm	65 nm	45 nm	32 nm	22 nm
Isolated Lines (in resist) [Physical gate, post-etch]	90 nm [65 nm]	53 nm [37 nm]	35 nm [25 nm]	25 nm [18 nm]	18 nm [13 nm]	13 nm [9 nm]
Chip Frequency	1.7 GHz	4.0 GHz	6.8 GHz	12 GHz	19 GHz	29 GHz
Transistors per chip (HV) (3 × for HP ; 5 × for ASICs)	100 M	190 M	390 M	780 M	1.5 B	3.1 B
DRAM Memory (bits)	510 M	1.1 G	4.3 G	8.6 G	34 G	69 G
Gate CD Control (3σ, post-etch)	5 nm	3 nm	2 nm	1.5 nm	1.1 nm	0.7 nm
Field Size (mm × mm)	25 × 32	25 × 32	22 × 26	22 × 26	22 × 26	22 × 26
Chip Size (mm) (2.2 × for HP ; to 4 × for ASIC)	140	140	140	140	140	140
Water Size (diameter)	300 mm	300 mm	300 mm	450 mm	450 mm	450 mm

*Semiconductor Industry Association (SIA), December 2001. ***Possible 2-year cycle.**

FIGURE 4. The international Technology Roadmap for Semiconductors[9] (ITRS) describes present and anticipated features of future nanoelectronic "chips." EUV lithography is expected to be used for the 45 nm and 32 nm "nodes." Shown above are representative expectation for both the published three-year cycle of dates, and the two-year cycle of dates projected by some leading edge manufacturers.

patterns anticipated, line widths in resist, isolated metal lines, anticipated number of transistors, clock speed, maximum field size, etc. The table is shown for both the released three-year cycle and also for a two-year cycle preferred by some leading edge manufacturers. It is anticipated that EUV lithography will be used in high volume manufacturing for the 45 nm and 32 nm nodes, in the years 2007 and 2009, respectively, following a two year cycle. The stepper is expected to use a six mirror, 0.25 NA stepper, operating at a 13–14 nm wavelength. The leading candidate EUV source, at this time, is a laser produced plasma expected to employ a high average power (~10 kW) diode pumped Nd laser and a liquid Xe jet, the latter selected largely for its low level of debris production. Alternate EUV source candidates within this spectral window are actively being pursued. These include a variety of electrical discharge plasmas, which typically offer good efficiency and power, but as yet unacceptably high levels of debris. The final source selected for production steppers will have to produce 60–80 watts of clean (debris free), collectable, in-band (within the multilayer bandpass of a nominally ten mirror stepper) EUV power with tight specifications for long life-time at high repetition rate (6–10 kHz). For an updated review of EUV source requirements and progress consult the International Sematech website concerning the most recent EUV Source Workshop[16] (November 2001, Matsue and October 2002, Dallas).

The most recent (Feb. 2002) summaries of EUV lithography were presented at the SPIE Microlithography Conference, in Santa Clara, CA. The published Proceedings[17] include reports on print experiments, optics, coatings, masks, resists, sources, environmental chemistry, etc. Scanned patterns[6] were presented with 100 nm lines and spaces printed across a full field of 26 mm by 32 mm, using a laser produced Xe jet plasma. Smaller "microfield" exposures, typically 100 μm across, were printed statically to 50 nm lines and spaces, with special illumination,[7] and isolated lines were printed to 39 nm, as shown in Figure 5. The 39 nm and 50 nm lines were printed using synchrotron undulator radiation, which is useful for metrology and special exposure studies, but is not a candidate source for production printing. The 39 nm isolated lines were printed in resist with 0.1 NA, four bounce optics. This bodes well for future production steppers which will employ 0.25 NA, six bounce optics, and thus should achieve 16 nm line widths in resist. Based on these expectations, anticipated progress with the source, resist sensitivity and line edge roughness (LER), and advances in defect free masks, it is expected that EUV lithography will be available for high volume production beginning in 2007. For those working in the EUV source area there are many opportunities to contribute, not only to the stepper (print) source, but also to development of a variety of specialized sources for metrologies of the optics, coatings, mask and mask blanks, etc.

CONCLUSION

Substantial progress has been presented in both soft x-ray microscopy and extreme ultraviolet lithography, in each case showing high quality images with clearly defined features in the 20–40 nm regime. The soft x-ray microscopy has now been extended to

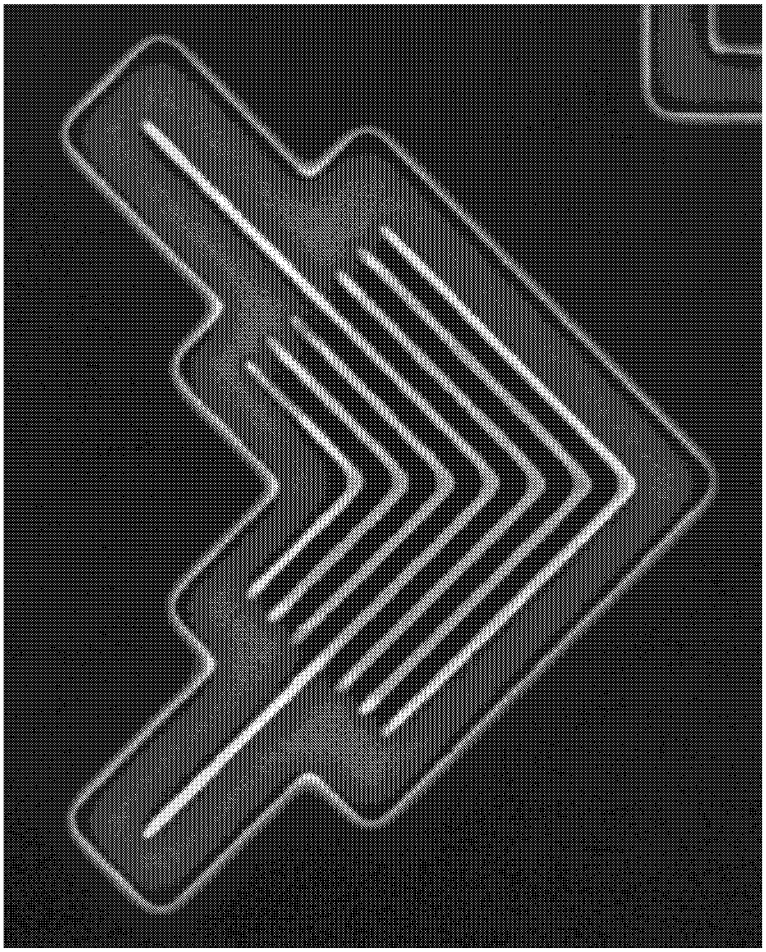

FIGURE 5. A static microfield EUV image of isolated and semi-isolated 39 nm wide lines, printed using the 0.1 NA ETS set 2 optics at 13.4 nm wavelength. Courtesy of Dr. Patrick Naulleau,[7] Lawrence Berkeley National Laboratory.

3D tomographical imaging and is poised to address significant issues in the physical and life sciences, while EUV lithography is rapidly maturing to the point that it is the favored technology for high volume manufacturing of 20 GHz microprocessors in the 2007 to 2009 time frame.

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