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High resolution full-field imaging of nanostructures using compact extreme ultraviolet lasers

F Brizuela[1], C Brewer[1], S Fernandez[1], D Martz[1], M Marconi[1], W Chao[2], E H Anderson[2], A V Vinogradov[3], I A Artyukov[3], A G Ponomareko[4], V V Kondratenko[4], D T Attwood[2], K A Bertness[5], N A Sanford[5], J J Rocca[1] and C S Menoni[1]

[1] NSF Engineering Research Center for Extreme Ultraviolet Science & Technology and Department of Electrical and Computer Engineering, Colorado State University, USA
[2] NSF Engineering Research Center for Extreme Ultraviolet Science & Technology and Center for X-Ray Optics. Lawrence Berkeley National Laboratory, USA
[3] P. N. Lebedev Physical Institute, Russia
[4] National Technical University "KhPI", Ukraine
[5] National Institute of Standards and Technology, Boulder, USA

E-mail: brizuela@engr.colostate.edu

Abstract. Recent advances in the development of high peak brightness table-top extreme ultraviolet (EUV) and soft x-ray (SRX) lasers have opened new opportunities for the demonstration of compact full-field EUV/SXR microscopes capable of capturing images with short exposures down to a single laser shot. We demonstrate the practical application of table-top zone plate EUV microscopes that can image nanostructures with a spatial resolution of 54 nm and below and exposure times as short as 1.2 ns, the duration of a single laser shot.

The development of compact full-field extreme ultraviolet (EUV) and soft x-ray (SXR) microscopes relies on the availability of compact illumination sources with sufficient brightness in this region of the electromagnetic spectrum. Several table-top EUV/SXR sources have been successfully used to demonstrate full-field zone plate microscopy including plasma sources, high-harmonic generation (HHG) and lasers [1-3].

We have demonstrated wavelength-scalable high resolution full-field microscopes based on two table-top EUV lasers developed at Colorado State University [4-6]. One microscope uses a compact desk-top capillary discharge laser that emits at 46.9 nm wavelength [7]. The laser emission is created in a highly ionized Argon plasma column generated by fast electrical discharge excitation. The laser output consists of highly monochromatic ($\Delta\lambda/\lambda \sim 5\text{x}10^{-5}$) pulses with ~10 μJ of energy (2.4×10^{12} photons/ pulse) at a repetition rate of up to 12 Hz. The degree of spatial coherence of the illumination can be varied with the length of the plasma column that constitutes the gain medium. The 22 cm long capillary selected for these experiments produces optimized, partially coherent illumination that limits speckle effects that can degrade image quality, while still providing sufficient photon flux for single shot imaging. This system can operate in transmission and reflection modes rendering images with spatial resolution as high as 54 nm with exposure times ranging from ~ 20 sec down to a single laser shot, equivalent to ~1 ns [4, 5].

The second microscope is based on a 13.2 nm wavelength table-top laser. The laser pulses are generated by the amplification of spontaneous emission in a transient population inversion produced by electron impact excitation in a transition of nickel-like cadmium ions [8, 9]. A 4 mm long plasma is created by heating a 4 mm wide Cd slab target with a sequence of pulses from a chirped-pulse-amplification Ti:Sapphire laser system. Operating at typically 5 Hz repetition rate, the EUV laser produces highly monochromatic ($\Delta\lambda/\lambda < 1\mathrm{x}10^{-4}$) pulses of 13.2 nm wavelength, 5 ps duration and ~200 nJ energy (~10^{12} photons/pulse) resulting in an average power of ~1 μW. This transmission microscope can obtain images with spatial resolution better than 38 nm with acquisition times of less than 20 seconds [6].

The optics in the microscopes is a combination of reflective and diffractive elements. The condenser in the 46.9 nm microscope is a Sc/Si multilayer coated Schwarzschild. The 13.2 nm wavelength microscope uses a Fresnel zone plate (FZP) condenser. The objectives in both systems are FZP with a typical efficiency of 5-10%. Specifically for the 46.9 nm microscope, a new freestanding zone plate technology that connects the circular zones with pseudo-random bridges was developed to reduce absorption and increase their efficiency [10]. The FZPs of the 46.9 nm microscope have outer zone widths of Δr=200 nm, 120 nm, 70 nm. The 13.2 nm microscope is equipped with zone plate objectives with Δr=80 nm and 50 nm. In both microscopes, the images are captured using a EUV sensitive back-illuminated CCD detector.

The spatial resolution of the microscopes was assessed by evaluating the intensity modulation of transmission gratings. EUV images of periodic gratings with half-periods down to 38 nm were analyzed to build the modulation transfer function (MTF) for every objective zone plate available. Figure 1 shows the MTF of the highest numerical aperture objective for each microscope along with grating images used to obtain the data. A spatial resolution of 54 nm was determined for the 46.9 nm wavelength microscope. With the 13.2 nm wavelength microscope we were able to clearly resolve the smallest patterns available on the sample with a half-period of 38 nm.

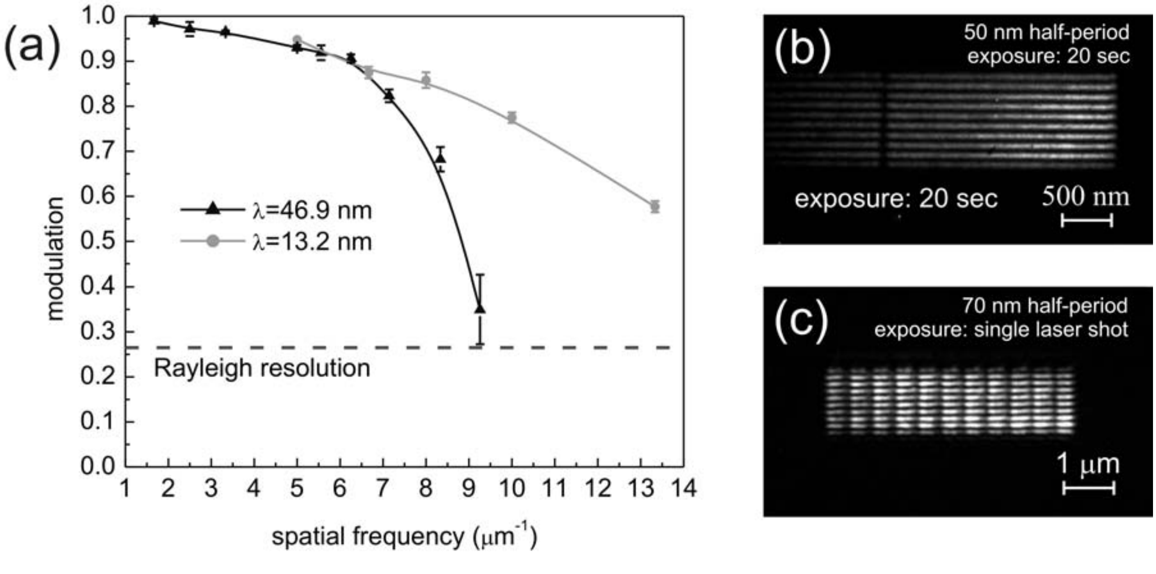

Figure 1. (a) Modulation Transfer Functions (MTFs) for the 46.9 nm microscope using the FZP objective with Δr=70 nm (triangles) and for the 13.2 nm microscope with the FZP objective with Δr=50 nm (circles). EUV images of gratings with a half-period of: (b) 50 nm and (c) 70 nm used to build the MTF shown in (a).

We have exploited the versatility of the 46.9 nm microscope to image a variety of nanostructures. Figure 2.a) is a reflection mode EUV image of a GaN nanowire connecting two Ti contacts grown on a Si wafer [11]. Figure 2 b) and c) are EUV transmission images of a diatom and a carbon nanotube, respectively that were deposited onto Si membranes. The EUV image of the diatom obtained with the Δr=120 nm FZP objective and an exposure of 5 seconds reveals a periodic pattern of 200 nm half-period. The 50 nm diameter carbon nanotube EUV image was captured with a single laser shot using the Δr=70 nm FZP. The flash imaging capability coupled with the ease in sample preparation make the microscope suited for tracing dynamics of such nanoscale systems.

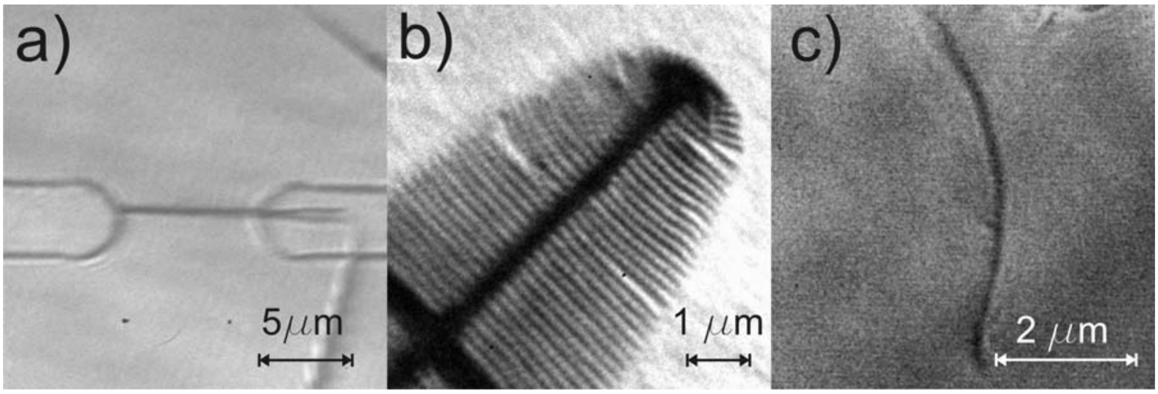

Figure 2. a) Reflection mode image of a GaN nanowire connecting two Ti contacts on a Si wafer. Transmission images of: b) a diatom and c) a carbon nanotube on a Si membrane. The latter was obtained with a single laser shot.

In summary we have demonstrated the practical use of EUV microscopes based on table-top EUV lasers to capture good quality images of nanoscale objects with exposures as short as a single laser shot. We anticipate that using recently developed shorter wavelength, high brightness, table-top lasers it will be possible for compact full-field microscopes to reach a spatial resolution approaching 15 nm with picosecond temporal resolution for a wide range of nanoscience and nanotechnology applications.

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