A tabletop, extreme ultraviolet (EUV) imaging system with nanometer-scale resolution has been developed. This system is based on a very compact capillary-discharge Ne-like Ar laser emitting in the EUV part of the spectrum at a wavelength of 46.9 nm. Imaging was demonstrated in both transmission and reflection modes to obtain a spatial resolution better than 140 nm. This is the best resolution obtained with a compact coherent source to date. These results, which are scalable to shorter wavelengths and higher resolution, foretell the feasibility of compact imaging tools to further developments in nanoscience and nanotechnology. Abilities of this microscope, such as investigating structural materials on nanoscales, aiding in the lithographic process of the next-generation of integrated circuits with nanoscale feature sizes, and “seeing” nanofeatures of miniature systems as they are designed, will allow spacecraft and space exploration techniques to reach a previously unsurpassed level.

Nomenclature

\[ k = \text{a constant that is dependent on the coherence of the illumination source and quality of the optics} \]
\[ \lambda = \text{wavelength of the illumination source} \]
\[ NA = \text{numerical aperture of the objective} \]
\[ \Delta r = \text{outer zone width of a zone plate} \]

I. Introduction

NANOTECHNOLOGY carries the undeniable promise to lead to previously unimaginable possibilities and discoveries in science and technology. According to NASA’s Center for Nanotechnology “Nanotechnology is the creation of functional materials, devices and systems through control of matter on the nanometer length scale (1-100 nanometers), and exploitation of novel phenomena and properties (physical, chemical, biological, mechanical, electrical...) at that length scale” (http://www.ipt.arc.nasa.gov/). As the science and technology take a journey into the nano-world, possibilities such as integrated circuits reaching feature sizes smaller than 100 nm, nanostructures being developed, and material properties on the nanometer length scale being discovered and manipulated, will be achievable. This nanoscience and nanotechnology revolution opens a myriad of opportunities for spacecraft design and space exploration techniques.

As nanotechnology rapidly progresses, compact, fast, and practical tools that allow us to “see” nanometer-scale features are highly desired. Several high-resolution imaging techniques currently exist, such as electron microscopy and various scanning probe techniques. An alternative method, optical microscopy, is advantageous to the other techniques in that the investigated sample requires little preparation, images are rendered rapidly, and the sample’s environment can be varied. (e.g., by varying the electromagnetic field to study the reactions of a material or

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biological specimen). Unfortunately conventional visible light microscopes are limited in resolution. The spatial resolution capability of a light microscope is given by the Rayleigh criterion,

\[
\text{Spatial resolution} = \frac{k \cdot \lambda}{NA},
\]

where \(\lambda\) is the wavelength of the illumination source, \(NA\) is the numerical aperture of the objective, and \(k\) is a constant that is determined by the objective’s aberrations and coherence of the source.\(^1\)\(^2\) For an aberration free objective and incoherent illumination, \(k = 0.61\). Spatial resolution is therefore limited to \(~200\) nm at best with a visible light source (\(\lambda = 400\) nm). The ability to resolve 100-nm scale features can thus be achieved by using shorter wavelength extreme ultraviolet (EUV) or even soft-x-ray sources.

The best resolution thus far, 20 nm, was obtained using 2.07 nm wavelength synchrotron radiation in transmission mode.\(^2\) This imaging system has been used to obtain spectacular images of biological cells, magnetic structures, and other objects with impressive quality and detail.\(^3\)\(^5\) Unfortunately the very small number and extremely high demand of synchrotron sources limits the widespread use of this powerful technology.

We have developed a more compact and practical high-resolution imaging system with a tabletop capillary-discharge pumped EUV laser source, which is only a small fraction of the size of a synchrotron. This system can be potentially used for imaging in nanotechnology applications and can be accommodated in a small-scale university lab or in an industrial setting, thus enabling much wider use of the nanoscale optical imaging. Unlike other existing EUV installations our microscope can operate not only in transmission mode, but also in the more challenging reflection mode. Due to low reflectivity of materials in the EUV part of the spectrum only one proof-of-principle experiment on the reflection mode imaging has previously been published.\(^6\) Our microscope is capable of this feature due to the high brightness of the source. This functional imaging system has successfully resolved features smaller than 140 nm,\(^7\)\(^8\) which is the highest resolution obtained to date using a compact coherent source. The resolution can be further improved beyond 100 nm by using the readily available higher resolution optics and shorter wavelength laser light.

![Figure 1. A schematic representation of the 46.9 nm compact extreme ultraviolet imaging system set up in transmission mode.](image)

II. Imaging System Setup

The high resolution microscope configured for transmission mode of operation is schematically depicted in Fig. 1. It consists of a compact EUV laser followed by a reflective Schwarzschild condenser, which focuses the light onto the sample. A diffractive zone plate objective then forms a magnified image of the sample onto an EUV-sensitive CCD detector. To implement the reflection mode of imaging the sample is turned at 45° with respect to the beam, whereas the objective and the CCD are placed in the reflected beam at 90°. The condenser, sample, and objective are all mounted on motorized translation stages and assembled in a vacuum chamber that is typically maintained at a pressure of ~10^(-5) torr.

A. Laser Source

A very compact capillary-discharge Ne-like Ar laser that emits radiation at a wavelength of 46.9 nm was used as the illumination source (Fig. 2). This laser that was recently developed at Colorado State University is the brightest source of coherent EUV light available today, with the average output power exceeding 3 mW. Lasing is obtained here by exciting a plasma column in a ceramic capillary with a fast 200 kA current pulse. The length of the capillary determines the laser output pulse energy and degree of spatial coherence. In this experiment a relatively short 18 cm capillary was used, providing a pulse energy of ~ 100 μJ. This choice of capillary length ensured a sufficient photon flux while keeping the spatial coherence of the laser beam relatively low to avoid diffraction fringes and speckle in the images. The laser pulses have duration of ~1.2 ns and a repetition rate of 1 Hz. This laser is well-suited for high resolution microscopy due to its short wavelength, high photon flux, narrow spectral bandwidth, and controllable spatial coherence.

B. Condenser

One of the specific features of the EUV spectral range is that even a thinnest layer of any material absorbs most of the EUV radiation. Therefore the conventional refractive lenses can not be used at EUV. Instead, only reflective, such as multilayer coated mirror, or diffractive, such as zone plate, optics can be used in the design of a microscope. A Sc/Si multilayer coated Schwarzschild objective was developed in this work to condense the light onto the sample. This Schwarzschild contains a primary convex mirror of 10.8 mm in diameter and a 50 mm secondary concave mirror. Together these two mirrors produce a hollow cone of 46.9 nm light that is focused onto the sample, which is placed ~2.5 cm from the output of the condenser. The Schwarzschild condenser has a numerical aperture (NA) of 0.18 and a throughput of only ~1%. This low throughput could be improved by at least one order of magnitude by using the best available Sc/Si multilayer coatings with ~40% reflectivity at this wavelength.10

C. Objective

A diffractive zone plate was used as an objective. A zone plate consists of alternating opaque and transparent concentric rings (Fig. 3). When the radiation skims the edges of the opaque regions it bends, or diffracts, at an angle that is directly proportional to the wavelength of the illumination and indirectly proportional to the zone width. Thus the smaller the zone width, the more the light bends. The radius of each of these rings is chosen such that the diffracted radiation has the same phase for constructive interference, and is directed towards a focal point. To achieve this, the radius of each subsequent transparent zone must have an optical path length difference towards the

Figure 2. A picture of the 46.9 nm imaging system with the tabletop capillary-discharge Ne-like Ar laser (right) and the microscope chamber (left).
A zone plate is advantageous due to its high spatial resolution capability and small size. The spatial resolution of a zone plate can be estimated as:

$$\text{Spatial resolution} \equiv 2 \cdot k \cdot \Delta r \cdot$$

where $\Delta r$ is the width of the outermost zone and $k$ has the same meaning as in Eq. 1.

The zone plate for this microscope was manufactured at Lawrence Berkeley National Laboratory using electron beam lithography in a thin nickel foil. Normally zone plates designed for shorter wavelength are supported by a very thin (~100 nm) silicon nitride ($\text{Si}_3\text{N}_4$) substrate. Because 46.9 nm radiation is rapidly absorbed by most materials, the zone plate for our imaging system was fabricated to be “freestanding” to maximize throughput. This was accomplished by adding random pseudo support structures connecting the rings and then etching out the substrate. Fig. 4 is a computer aided design (CAD) image of a freestanding zone plate. It has an outer zone width of 200 nm, a diameter of 0.5 mm, a focal distance of 2.13 mm, and a numerical aperture of 0.12.

The reason a zone plate was not used as the condenser instead of the Schwarzschild objective, which is large and has a throughput of only ~1%, is that it was impossible to manufacture a sturdy freestanding zone plate large enough to encompass the beam diameter at the condenser position, which was approximately 10 mm.

![Figure 3. An illustration of a diffractive zone plate. (from Ref. 11)](image1)

![Figure 4. A CAD image of a “freestanding” zone plate with pseudo-random support structures connecting the zones.](image2)

### III. Results

To investigate the capabilities of the new imaging system we have tested it with a few samples with nanometer-scale features. The first sample imaged was a specially designed test pattern containing concentric apertures as small as 100 nm. It was fabricated using electron beam lithography onto a nickel foil. Fig. 5(a) is an image of the test pattern acquired in transmission mode with a magnification of 470x. The illuminating beam was focused to a 20-30 µm diameter spot on the sample, and the laser was shot 10 times at a 1 Hz repetition rate, resulting in an exposure time of 10 s. An image obtained with the microscope set up in the reflection mode configuration at a magnification of 480x is shown in Fig. 5(b). To ensure complete illumination of the sample and reduce coherence effects in the image, the condenser was slightly defocused and its position was continuously scanned during the acquisition of 70 laser shots. Because the beam is not at normal incidence with respect to the sample, and the zone plate has a narrow focal depth of ~3.5 µm, only the central vertical portion of the image is well defined. The smallest 100 nm apertures in the inner circle are visible in both images.

To illustrate one of the applications of reflection mode imaging, the second sample imaged in reflection mode was chosen to be a silicon wafer chip with patterned polysilicon lines. This chip was manufactured in an effort...
aimed towards optimizing the lithography process for chip manufacturing. Fig. 6 is an EUV image of the silicon sample acquired using 20 laser shots with a 480x magnification. In the upper right corner of the image, 100 nm polysilicon lines spaced by 800 nm are discernible. However, the line-width appears larger than 1/8 the value of the spaces, which is an indication that the 100 nm finest lines are narrower than the resolution limit of this system. In the lower right region of the image, 250 nm lines and spaces are well resolved.

To determine the spatial resolution of the 46.9 nm wavelength microscope, an extra freestanding zone plate was imaged in transmission mode. Images were acquired at a magnification of 250x for the larger periodic circles toward the center of the zone plate (Fig. 7(a)), while a magnification of 750x was chosen for the smaller zones of 200 nm near the edge of the zone plate (Fig. 7(b)).

Periodic structures are often used to determine the spatial resolution of a microscope. Here the size of the periodic zones at which the peak intensity modulation is reduced to 26.5%, according to the Rayleigh criterion, is the resolution of the microscope. In these images, the intensity distribution of the smallest 200 nm zones at the edge of the zone plate still had a modulation depth of more than 90%. In the absence of a finer periodic structure a different, the knife-edge resolution test, was then applied. This test calculates the distance it takes at the edge of a structure for the intensity to drop from 90% to 10%. To apply this test, we took a typical cross section of the intensity distribution at the edge of the zone plate and found a local resolution of 126 nm, illustrated in Fig. 7(c).

Figure 5. Images of a sample test pattern obtained with a compact 46.9 nm wavelength microscope in (a) transmission mode with a 10 second exposure time, and in (b) reflection mode with a slightly longer exposure time of 70 seconds to compensate for the low reflectivity of the Ni test pattern. The inner circle apertures are 100 nm wide.

Figure 6. A reflection mode image of a silicon wafer chip acquired in 20 seconds at a magnification of 480x. The lines in the upper right corner are 100 nm wide spaced apart by 800 nm, and in the lower right corner are 250 nm wide lines and spaces.
Averaging together 25 different areas along the edge of the zone plate, the spatial resolution of the system was realized to be 137 ± 15 nm. This is the best resolution ever obtained with a compact coherent illumination source.

Referring to Eq. (1) for determining the resolution limit of a light microscope and plugging in \( \lambda = 46.9 \) nm for the illumination source wavelength, \( NA = 0.12 \) for the numerical aperture of the imaging zone plate, and \( k = 0.61 \) for the constant of an aberration-free zone plate and an incoherent illumination source, the estimated spatial resolution capability of our microscope is 238 nm. However, the experimentally determined resolution of this system was 137 ± 15 nm, which corresponds to \( k = 0.35 \). This low value for \( k \) is a result of partially coherent illumination of the sample and low aberrations in the imaging zone plate.\(^7\)

Figure 7 (a) A transmission mode image at the edge of a freestanding zone plate with 200 nm outermost zones. It was obtained using the 46.9 nm wavelength microscope in transmission mode with 10 laser shots at a magnification of 750x. (b) A sampled crosssection of the intensity distribution at the edge of the zone plate’s image. According to the knife-edge test, the 10-90% transition local resolution is 126 nm. An average of 25 different areas along the edge of the zone plate resulted in a resolution of 137 ± 15 nm.

IV. Current Work

According to Eq. (1), the most direct way to improve spatial resolution of an imaging system is to use a shorter wavelength illumination source. Recently a small-scale laser-pumped Ni-like Ag laser with an output wavelength of 13.9 nm was developed at CSU (Fig. 8).\(^5\) This novel source produces very short pulses of light at 13.9 nm

Figure 8. A picture of the recently-developed, small-scale, laser-pumped, Ni-like Ag laser with an output wavelength of 13.9 nm.
wavelength as a result of ionization and heating silver plasma with high energy pulses from an infrared laser. We are currently developing a new imaging system that would work with this laser and that would have a sub-100 nm spatial resolution.

The new imaging system is similar to the 46.9 nm wavelength system in Fig. 1. One difference is that because silicon nitride is not as absorbant at a wavelength of 13.9 nm, it is unnecessary for the zone plates to be freestanding. This combined with the fact that the 13.9 nm beam is smaller at the location of condenser allowing for a smaller condenser, makes it possible to manufacture sturdy zone plates for both the objective and condenser.

A star test pattern consisting of converging thin nickel lines supported by a Si$_3$N$_4$ substrate has been imaged in a preliminary experiment. Fig. 9 is an image of this pattern acquired with an exposure time as short as 20 seconds. The central part of the pattern shows lines of about 80 nm. This first imaging result demonstrates the feasibility of imaging with this newly developed EUV laser, and indicates the ability of this instrument to resolve feature sizes below 80 nm.

![Figure 9](image.png)

**Figure 9.** An image of a set of radial spokes obtained using 13.9 nm wavelength illumination with a 20 second exposure. The lines visible in the center of the pattern are ~80 nm wide.

V. Conclusion

In conclusion, we have achieved high resolution, real-time imaging in both transmission mode and the more challenging reflection mode by exploiting the high photon flux and high repetition rate of a capillary-discharge EUV laser emitting radiation at the short wavelength of 46.9 nm. The imaging system employs a Schwarzschild condenser, zone plate objective, and a CCD detector to resolve feature sizes as small as $137 \pm 15$ nm. This result is impressive, as it is the best resolution ever obtained using a compact coherent EUV source.

To achieve even better resolution, we are currently developing an imaging system that relies on the recently demonstrated 13.9 nm laser. By using an illumination source with a wavelength less than 1/3 of the 46.9 nm wavelength source, we expect to achieve a spatial resolution significantly better than 80 nm.

Our future goals are to improve the performance of the imaging system using a better understanding of coherence effects, using zone plates with smaller outer zone widths, and moving to shorter wavelengths as compact sources are developed. We also plan to further scale down the size of the imaging system, thus making it more attractive for practical applications.

These efforts are significant, as they will pave the way to realize a high-resolution, real-time, compact imaging tools for many applications. By investigating nanoscale properties of materials and systems, inspecting lithographic masks to produce integrated circuits with nanoscale feature sizes, and overall aiding in the development of nanoscience and nanotechnology, these instruments will serve as an important aide in advancing the space exploration and spacecraft design.
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