Demonstration of Nanomachining With Focused Extreme Ultraviolet Laser Beams

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(Invited Paper)

***Abstract*—A major challenge in laser machining of microstructures is that of extending the spatial domain to the smaller dimensions of interest in nanotechnology. We demonstrate the feasibility of directly machining nanoscale structures with a focused extreme ultraviolet (EUV) laser beam. Clean sub-200–nm-wide trenches (130-nm full width at half maximum) were ablated on polymethyl methacrylate photoresist by focusing the 46.9–nm wavelength beam from a Ne-like Ar capillary discharge tabletop laser with a Fresnel zone plate lens. Considering that clean 82-nm holes were also ablated using the same laser, it can be expected that focused EUV laser light will enable the machining of significantly smaller features.**

***Index Terms*—Extreme ultraviolet (EUV) lasers, laser ablation, nanomachining, nanotechology.**

I. Introduction

Advances in nanotechnology motivate the extension of laser machining of microstructures to the smaller dimensions of interest to nanotechnology. Optical lasers are widely used for micromilling and micro hole drilling. [1], [2]. The size of the smallest features that can be created focusing intense laser beams onto materials is limited mainly by the laser wavelength and by the diffusion of heat. A variety of different techniques have been developed to overcome the limitations imposed by the diffraction limit in order to produce ablation craters of subwavelength size using optical and ultraviolet (UV) lasers [3]–[8]. Craters with subdiffraction-limit sizes were produced using UV light by taking advantage of the well-defined ablation threshold in materials [3]. Femtosecond laser pulses in the visible [4], near infrared [5], and UV [6] spectral regions were shown to produce ablation craters as small as 200 nm. A spatial resolution of 10 nm has been achieved with femtosecond optical laser pulses using the field enhancement that occurs at the tip of an atomic force microscope (AFM) or using optical fibers to create near-field effects [7]. The focusing of intense extreme UV (EUV) and soft X-ray laser pulses into much smaller spots combined with the short absorption depth of EUV light in most materials results in a superior localization of the energy. This opens the possibility to extend direct laser machining into significantly smaller dimensions. This is presently a particularly attractive possibility considering that compact $\lambda = 46.9$ nm wavelength desktop-size EUV lasers are now available [9].

An experiment was reported in which 10-nm wavelength incoherent light from a Ta laser-created plasma was used to irradiate silica plates covered with a WSi contact mask producing 70-nm trenches [10]. However, this approach to nanomachining requires the fabrication and later the removal of a patterned contact mask containing the desired nanoscale features. We have previously ablated clean holes as small as 82 nm in diameter on polymethyl methacrylate (PMMA) focusing single laser shots from a tabletop 46.9-nm wavelength capillary discharge laser [11]. This result suggested the possibility of directly machining nanostructures with focused EUV/soft X-ray laser beams. Herein, we demonstrate the feasibility of such scheme performing for the first time maskless nanoscale machining of trenches on polymers with a focused EUV laser beam. We ablated sub-200-nm-wide trenches several micrometers in length into PMMA.

Several experiments have been reported that studied the ablation of materials by intense EUV and soft X-ray light using different light sources [12]–[16]. The interaction of intense EUV light with materials is fundamentally different to that corresponding to longer wavelength light [17]. Long wavelength laser ablation is a threshold process in which the ablation rate is controlled by a threshold fluence. This threshold effect is particularly effective in ablation with subpicosecond pulses [8]. In contrast, at EUV wavelengths, the energy of a single photon is sufficient to induce damage in a polymer. Previous ablation experiments of organic polymers with this 46.9-nm laser show that ablation at this wavelength differs from that corresponding to irradiation with longer wavelengths, showing no well-defined ablation threshold [12]. It has been suggested that the key process is likely to be a radiolysis of the polymer chains by the

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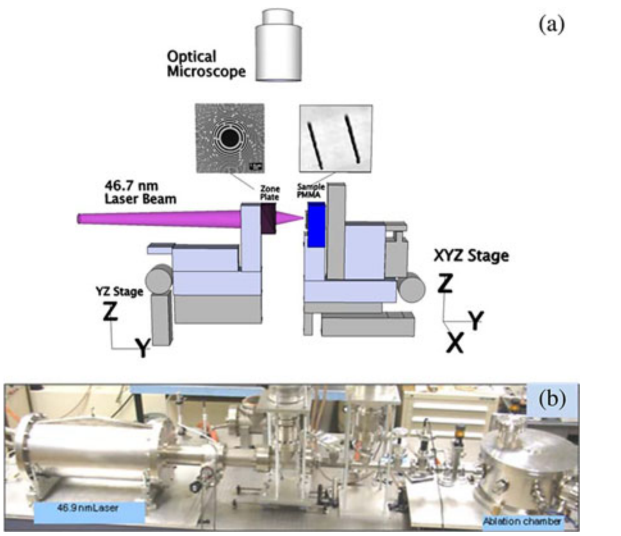

Fig. 1. (a) Schematic representation of the setup used to demonstrate EUV laser nanomachining. The output of a 46.9-nm capillary discharge EUV laser is focused with a FZP lens onto the sample. (b) Photograph of the nanomachining laser system showing the 46.9-nm capillary discharge laser (left) is attached to the processing chamber (right).

EUV photons [12]. Chain scissions are dominant processes in polymer materials irradiated with short wavelength light, resulting in the formation of molecular fragments that are ejected into vacuum or that are subsequently removed from the surface of the samples. Moreover, the fact that the critical density of $\lambda = 46.9$ nm light ($n_{ec} = 5 \times 10^{23}$ cm^{-3}) exceeds solid density implies that the EUV light is mostly absorbed in the solid target as opposed to near the critical density region of the plasma, as is the case for visible or UV laser light. The strong absorption of EUV radiation by most solid materials (e.g., 19 nm for $\lambda = 46.9$ nm in PMMA) results in a high degree of localization of the energy [18]. The high photon energy of the EUV photons exceeds the ionization energy of all neutral atoms and most low charge ions, resulting in direct single photon ionization, an absorption mechanism unavailable for optical wavelength lasers. A previous experiment that studied the interaction of EUV laser light with three different polymers showed that these unique interaction properties result in high-quality ablated surfaces, even upon irradiation with relatively long nanosecond pulses [13]. This, coupled with the inherent ability of EUV light to be focused into unprecedented small spots may constitute an advantage for the direct machining of nanostructures.

II. Experimental Setup and Procedure

Fig. 1(a) shows the schematic diagram of the experimental setup used to demonstrate nanomachining with a focused EUV laser beam. A photograph of the setup showing the EUV capillary discharge laser and the processing vacuum chamber is displayed in Fig. 1(b). Ablation is produced using a Fresnel zone plate (FZP) to focus pulses from a compact $\lambda = 46.9$ nm capillary discharge laser onto a Si wafer coated with PMMA. The laser [left on Fig. 1(b)] produces pulses by the amplification of spontaneous emission in a dense plasma of eight times ionized argon atoms (Ne-like Ar) created by injecting a fast current pulse into a capillary tube filled with argon gas [19], [20]. The fast current pulse rapidly compresses the plasma column to produce a population inversion and amplification in the 46.9-nm transition of Ne-like ions (26.4 eV photon energy). For this experiment, an alumina capillary discharge tube 27 cm in length and 3.2 mm inner diameter was used. The capillary discharge parameters were selected to produce ~0.1 mJ laser pulses of ~1.2 ns duration at a repetition rate of 1–2 Hz.

The FZP lens was manufactured on a thin silicon nitride membrane using electron beam lithography [21]. The structure was etched to make the FZP free standing for the purpose of increasing throughput at 46.9 nm. The FZP has a 0.5 mm diameter, an outermost zone width of 200 nm, and a numerical aperture NA = 0.12. Its Rayleigh-like spatial resolution in the first diffraction-order focus at 46.9-nm wavelength is ~ 240 nm. The zone plate was mounted on an XYZ translation stage and positioned at ~1.2 m distance from the capillary tube exit, where the laser beam diameter is ~6.5 mm. At this location, the beam significantly overfills the 0.5-mm aperture of the zone plate, and therefore only a small portion of the laser beam energy is incident upon the surface of the focusing optic. The first-order efficiency of the zone plate is ~10%. The third-order focus contains only ~10% of the energy of the first-order focus. The fluence onto the sample was further reduced by introducing a selected pressure of argon gas into the processing chamber as a mean of attenuating the beam by photoionization of the argon atoms by the 24.6 eV laser photons

In our previous crater ablation experiment with focused EUV laser pulses, the smallest diameter craters were obtained placing the sample at 7 μm from the plane of the third-order focus [11]. In principle, the spot diameter at that location should be three times smaller than at the first-order focus. However, because the zone plate used in the experiments was corrected for spherical aberrations in the first-order focus but not in the third, this was not the case. Nevertheless, it was found that at several micrometers of the location of the third-order focus, the beam intensity distribution is characterized by a narrow central peak ~100-nm full width at half maximum (FWHM) surrounded by several concentric rings of decreasing intensity. Attenuation of the beam intensity in the rings to the point at which the beam did not cause significant material removal allowed the creation of the smallest craters, 82 nm in diameter [11]. An atomic force microscope (AFM) image of a crater ablated in PMMA using this technique to focus a pulse from a 46.9-nm capillary discharge is illustrated in Fig. 2. A similar procedure was used to produce the trenches reported in this paper.

The sample was positioned into a kinematic mount, which was magnetically attached to an XYZ stage to ensure that it is placed back at the same position after it is removed for inspection. In this configuration, the sample can be displaced ±12.5 mm in the X and Y directions with up to ±1 μm resolution. The surface of the sample was aligned at 90° with respect to the laser beam. The displacement in the direction perpendicular to the beam axis Z was accomplished by means of a closed-loop piezoelectric actuator that has a resolution of ~50 nm. The sample consisted of an ~90-nm-thick layer of PMMA (MicroChem, 950000 molecular

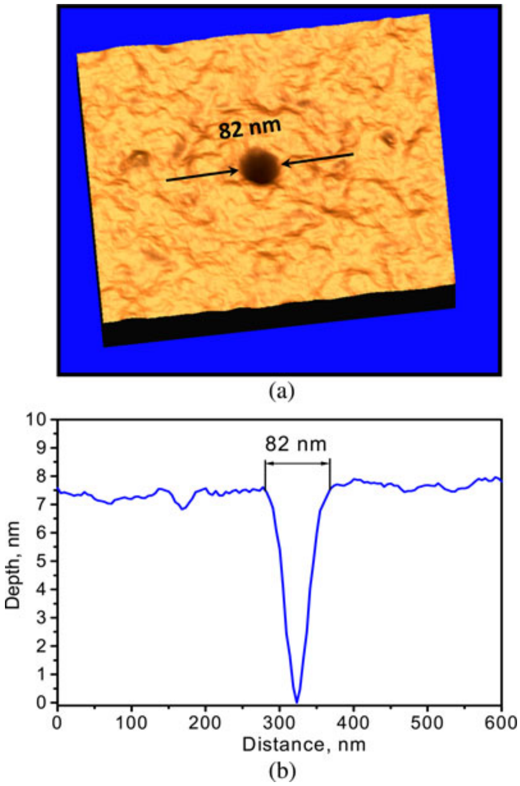

Fig. 2. AFM image (top) and lineout (bottom) of a 82-nm diameter hole ablated on PMMA by a single shot from a 46.9-nm laser. The sample was placed at 7 μm from the third-order focal plane of the one plate (from [10]).

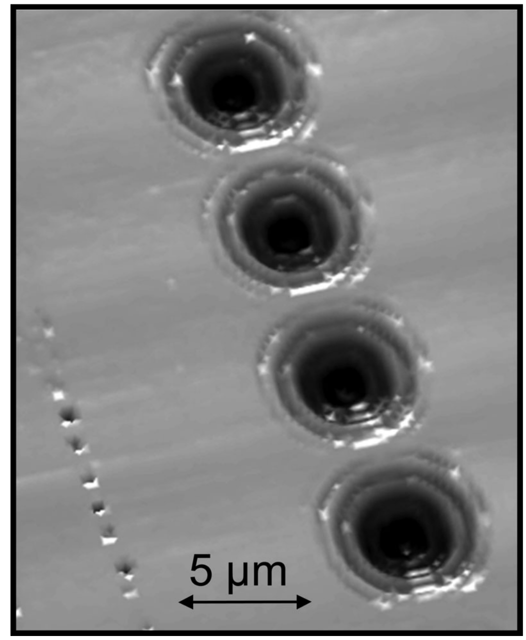

Fig. 3. AFM image of ablation craters produced by EUV laser ablation in PMMA using the unattenuated beam with first diffraction-order focusing (far right, unoptimized sample position) and third diffraction-order focusing (center and left).

weight) coated onto a silicon wafer. The sample was first prepositioned with the aid of a 10$\times$ visible light microscope at a distance of $\sim$2.1 mm from the lens corresponding to the first diffraction-order focal distance of the 200-nm outer zone width FZP. Trenches were ablated on the PMMA layer by moving the sample along Z with the piezoelectric actuator at a velocity of $\sim$50 nm/s while the laser was fired at 1- or 2-Hz repetition rate. The ablated patterns were analyzed with an AFM used in tapping mode with a 10-nm radius and 30° cone angle cantilever tip (MicroMasch, NSC16).

III. Nanomachining Results

Ablation craters, as shown on the right in Fig. 3, were obtained without attenuating the laser beam by placing the sample near the first-order focus of the zone plate. Inspection of the sample with an AFM showed that craters were produced when the sample was positioned as far away as $\pm 25\,\mu$m from the calculated focus. Depending on how close the sample was to the first-order focal plane, the craters diameter varied between 1 and 5 μm. Since these unoptimized first diffraction-order craters were easily obtained and could be located with a visible light microscope, they were used as a reference to find the smaller craters that were created positioning the sample near the third diffraction-order focus of the zone plate.

Ablation at the third-order focus was realized by initially prepositioning the sample with a 10$\times$ visible light microscope at a distance approximately equal to the third diffraction-order focal distance of the zone plate, 0.71 mm. Fig. 4 shows an AFM image of trenches machined when positioning the sample at different distances from the third-order focus of the zone plate lens. Each trench was ablated after repositioning the sample at steps of approximately 1 μm. Without the attenuation of the EUV laser beam, the entire thickness of the PMMA layer was ablated by a single laser shot, with the trenches reaching the surface of the silicon wafer. Without beam attenuation, concentric rings are noticeable surrounding the trenches. With sufficient beam attenuation, the rings are no longer observed, making it possible to obtain clean narrow trenches. For this purpose, several experimental runs were conducted attenuating the EUV laser beam by introducing argon gas into the path of the laser. Attenuation of the beam results in a reduction of the width and depth of the trenches, and no visible surrounding ablation rings. Fig. 5 shows trenches ablated while attenuating the beam by a factor of 8. As the sample was moved away from the focal plane, the width of the trenches decreased, as shown from right to left in Fig. 5. The average widths at the surface are 250, 280, and 295 nm. The respective average FWHMs starting from the left-most groove are 160, 180, and 182 nm. At this level of attenuation, the entire thickness of the PMMA layer is still ablated, with the grooves reaching the surface of the silicon wafer [Fig. 5(b)].

With an increased attenuation of the laser beam, $\sim$16$\times$, trenches with narrower widths were achieved. Fig. 6 shows a set of trenches ablated under this condition. The average widths at the surface of PMMA, starting from the left-most groove are $\sim$200, 250, and 270 nm. The corresponding FWHM are $\sim$130, 135, and 145 nm. The trenches are observed to have cleanly cut walls and sharp edges that are not affected by thermal damage. This is a result of the strong localization of the absorbed energy.

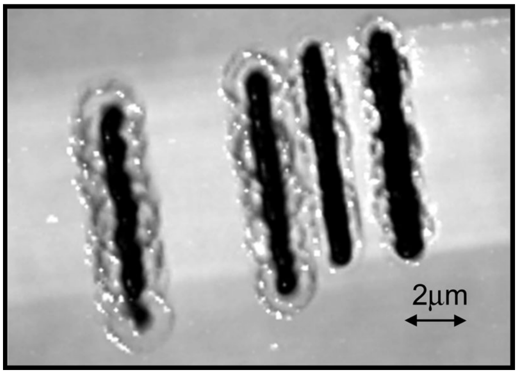

Fig. 4. Trenches machined on PMMA with the unattenuated 46.9-nm laser beam by positioning the sample at four different distances near the first-order focal plane. The left-most trench has an average width of 1 μm, and the diameter of the surrounding rings approach 2 μm.

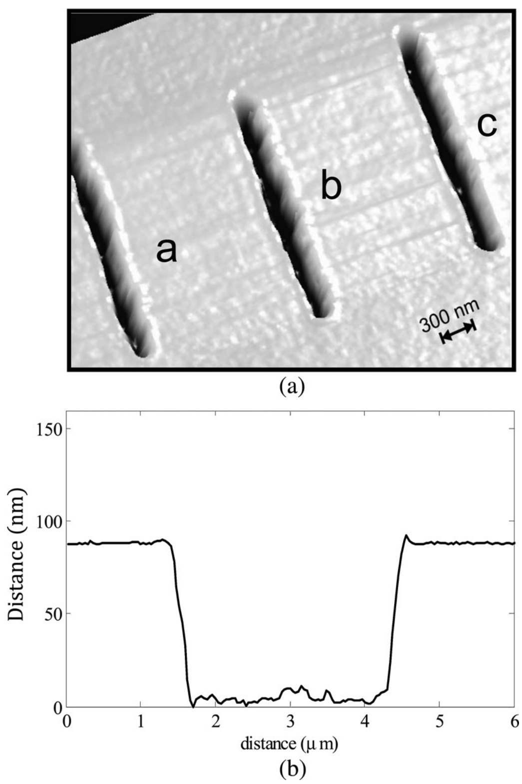

Fig. 5. Trenches machined on PMMA with a 46.9-nm laser beam positioning the sample at three different distances from the third-order focus of the zone plate and attenuating the beam by $\sim 8\times$. (a) Cross-section of the grove on the left along its length. The groove a has a FWHM of 160 nm and a width at the surface of 250 nm. (b).

Both the absorption length of the 46.9-nm light (19 nm) and thermal diffusion lengths ($\sim$10 nm) are short. The observed line edge roughness along the grooves is the result of shot-to-shot variation of the laser pulse energy with a possible contribution from laser beam pointing instabilities. Fig. 6(b) shows a lineout across the grooves. The depth of the trenches is observed to increase from 22 to 30 nm as the sample plane moves closer to the calculated focus.

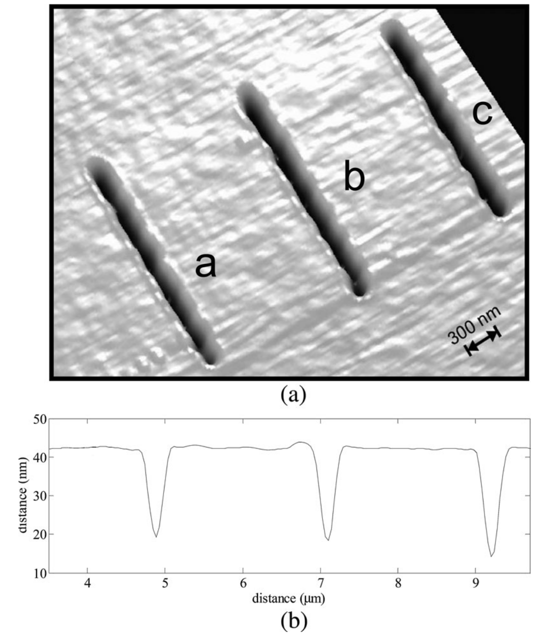

Fig. 6. Trenches machined on PMMA with a 46.9-nm laser beam by positioning the sample at three different distances from the third-order focus of the zone plate attenuating the beam by $\sim 16\times$. The groove on the left has an FWHM of 130 nm and a width at the surface of 200 nm.

In a first step toward machining metals, insulators, and semiconductors, our group has recently used a similar setup to ablate small holes in thin films of gold and hafnium oxide, and in silicon wafers.

IV. Conclusion

The results demonstrate for the first time the feasibility of directly machining of nanoscale features with a focused EUV laser beam. Sub-200-nm-wide trenches with cleanly cut walls and sharp edges not affected by thermal damage were machined in PMMA. Parameter optimization of this 46.9-nm wavelength laser ablation setup should result in the direct patterning of sub-100-nm features. Moreover, the recent demonstration of high repetition rate tabletop lasers that generate picosecond pulses with energies up to 10 μJ in the 13-nm spectral region [22] and >1 μJ at 10.9 nm [23] should further reduce the minimum achievable feature size. The combination of these short wavelength lasers with state-of-the-art zone plate optics with smaller outer zone width [24] may allow the direct machining of features sizes approaching 10 nm.

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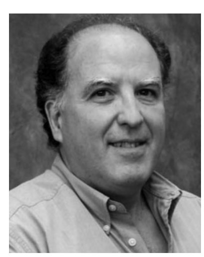

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Dr. Rocca received a Distinguished Lecturer Award from IEEE in 2006. He is the 2011 recipient of the American Physical Society Schawlow Prize in Laser Science. Early in his career, he was a National Science Foundation Presidential Young Investigator. He is a Fellow of the American Physical Society and the Optical Society of America, and a member of the National Science Foundation Engineering Research Center for Extreme Ultraviolet Science and Technology.