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Sculpted pulsed indium atomic beams via selective laser ablation of thin film

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Abstract

We present a novel experiment for the generation of sculpted pulsed indium atomic beams of regular arrays in one and two-dimensions via rear side ablation of indium by two and four beams interference pattern using second harmonic of high power Nd: YAG laser under high vacuum (10^{-5} Torr).

Keywords: High power interferometer; Laser ablation; Sculpted pulsed atomic beams.

INTRODUCTION

Pulse laser ablation technique is used in various applications (Trusso *et al*., 2005; Gamaly *et al*., 2005; Fernandez *et al*., 2005; Bruneau *et al*., 2005), in mechanical industry (Wieger *et al*., 2006), in medicine, in thin film deposition (pulsed laser deposition): (Chirsey & Hubler, 1994); lithography (Khare *et al*., 2004; Nakata *et al*., 2002, 2004), and production of atomic beams (Chae & Park, 1997; Breton *et al*., 1980; Kadar-Kallen & Bonin, 1994; Alti & Khare, 2006*a*). Pulsed laser ablation techniques for the production of atomic beam (Chae & Park, 1997; Breton *et al*., 1980; Kadar-Kallen & Bonin, 1994) have an advantage over thermal oven system, as they are not restricted to the materials of low melting points. It has ability to produce high atomic flux with energies from cold to super-thermal range. There are reports on production of atomic/molecular as well as ionic beams by ablation of solid targets (Chae & Park, 1997), thin foil (Breton *et al*., 1980), or thin film (Kadar-Kallen & Bonin, 1994; Alti & Khare, 2006*a*) using focused high power laser. Whenever a high power laser is focused on a target material, the laser fluence or the intensity at the focal spot is very large, and therefore substantial portion of the material ejected out from the target is converted into the plasma, and the expansion of the material is hemispherical (Alti & Khare, 2006*a*; Anan'in *et al*., 1991; Weaver & Lewis, 1996; Mishra & Thareja, 1999). Therefore, the divergence of the atomic beam generated by focused laser ablation is very large and depends on the laser fluence. Recently, we reported (Alti & Khare, 2006*a*) low divergence cold pulsed atomic beam of indium by rear side direct (unfocused) illumination of thin film by second harmonic of high power Q switched Nd: YAG laser. In that report (Alti & Khare, 2006*a*), we also compared the divergence of the atomic beam with and without focused laser beam.

In this paper, a novel experiment utilizing two and four beams interference pattern for the generation of large number of one- and two-dimensional arrays of atomic beams are reported. The interference pattern is periodic in nature, consisting of alternate dark and bright fringes. On illuminating with the interference patterns of a high power laser, the material of the thin film is ablated from the periodic region of bright fringe only, resulting into the arrays of atomic beams. If the interference pattern is in the form of straight parallel fringes, obtained from superposition of two coherent light beams, then the sculpting of the atomic beam is in one dimension. For the interference pattern of equal illuminating arrays of bright spots arranged in square geometry, obtained from the interference of four beams (Patra & Khare, 2006), the sculpting of the atomic beam is in two dimensions.

EXPERIMENTAL DETAILS

A Michelson interferometer as shown in Figure 1 was assembled with high damaged threshold beam splitter BS_1 and two mirror M_1 and M_2 for one-dimensional lithography. The interferometer was illuminated with second harmonic

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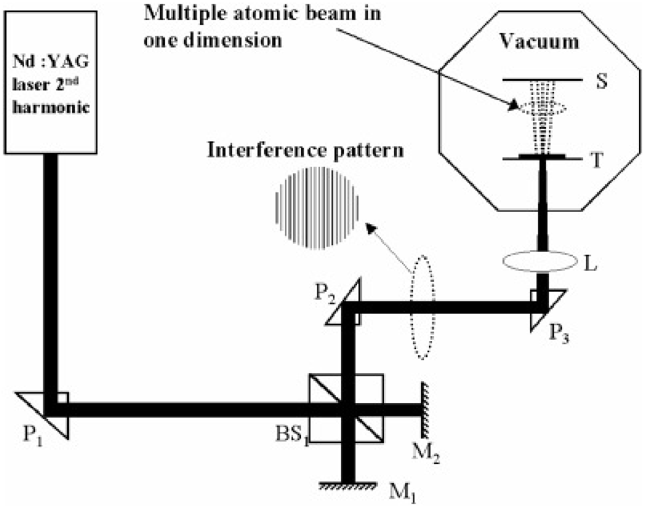

Fig. 1. Schematics of experimental set-up used for the generation of sculpted atomic beams in one dimension. $P_{1\text{-}3}$; Prism, BS_1; Beam Splitters, $M_{1,2}$; Mirrors, L; Lens, T; Target Indium thin film and S; Substrate.

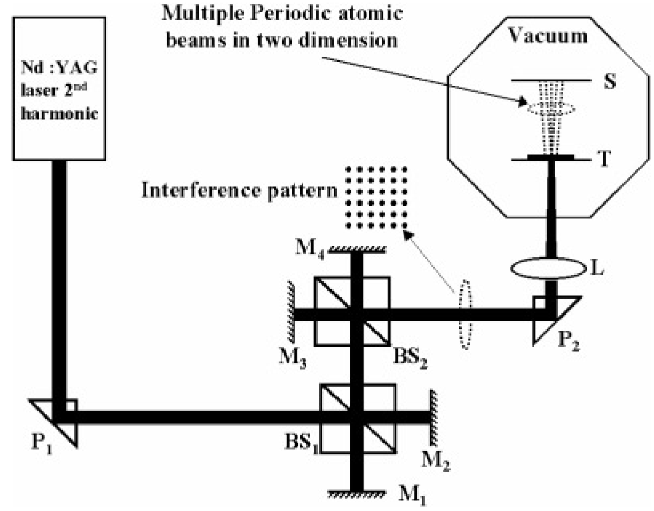

Fig. 2. Schematics of experimental set-up used for the generation of sculpted atomic beams in two dimensions. $P_{1,2}$; Prism, $BS_{1,2}$; Beam Splitters, $M_{1\text{-}4}$; Mirrors, L; Lens, T; Target Indium thin film and S; Substrate.

of high power Q-switched Nd: YAG laser (400 mJ in fundamental, 8 ns pulse width, beam diameter 8 mm, model HYL101 Quanta System) with the help of a 90° prism P_1. The output of this interferometer consists of straight-parallel fringes, as shown in Figure 1. Periodicity of this pattern depends on the angular separation between two interfering beams, which can be controlled by adjusting the tilt of one of the mirror online. This interference pattern was steered with the help of two 90° prisms, P_2 and P_3, as shown, into the vacuum chamber ($\sim 10^{-5}$ Torr) through a 50KF view port attached to it, to illuminate the thin film of indium, mounted inside the chamber, from the rear side. The thin film of indium was fabricated by depositing the indium vapors on to the cleaned microscopic glass slides by thermal evaporation under a base pressure of 10^{-6} Torr. For obtaining the smaller periodicity of arrays of atomic beams, the interference pattern was compressed with the help of a lens L (focal length = 25 cm), such that the distance between the lens and thin film was 31 cm. The rear side illumination of thin film by second harmonic of Nd: YAG laser results into the ablation of indium in the region of bright fringe leaving the area of dark fringe unaffected. The thin film was moved vertically to obtain the fresh region of the material for every shot of Nd: YAG laser. The morphology of the planer parallel atomic beams will be similar to that of the interference pattern. A glass substrate was kept parallel to and 14.5 mm away from the thin film to deposit atomic beams for the topographical analysis. The substrate and target were scanned with the optical microscope.

For bi-directional sculpting of atomic beams, two Michelson interferometers in tandem were aligned with the help of four mirrors ($M_{1\text{-}4}$) and two beam splitters ($BS_{1\text{-}2}$) as shown in Figure 2. Beam splitter BS_1 and mirrors M_1 and M_2 form the first stage of the interferometer similar to Figure 1 giving the two interfering beams. These two beams were launched into the second Michelson interferometer comprising of BS_2, M_3, and M_4. The output of the BS_2 consisted of four nearly collinear interfering beams. The mirrors tilts were adjusted to obtain the interference pattern of these four beams in the form of arrays of equal illuminating bright spots in square geometry (Patra & Khare, 2006), as shown in Figure 2. This pattern of equal illuminating light spot was steered into the vacuum chamber, with the help of prism P_2 and after the compression with the lens L, for the generation of sculpted arrays of atomic beam in two dimensions via rear side ablation. The rear side illumination of thin film by this interference pattern of second harmonic of Nd: YAG laser results into the ablation of indium in the region of bright spot only. The periodicity and geometry of the resultant atomic beams in the transverse plane have similar two-dimensional morphology as that of the interference pattern. These atomic beams were deposited on the glass substrate placed 15 mm away from the target for the topographical analysis of beams. The substrate and target was scanned with the AFM (Smena B, NTMDT). The interfering beams from the set-ups of Figure 1 and Figure 2 were almost collinear; thereby the interference patterns were highly de-localized. Therefore, location of the target is not critical with respect to the output beam splitter.

RESULTS AND DISCUSSIONS

The scan images of target T exposed to the single shot of two beams interference pattern of Figure 1 is shown in Figures 3a and 3b. The laser fluence on to the target was ~ 300 mJ/cm^2. Figure 3a shows the complete pattern imprinted onto the target and Figure 3b shows the corresponding micrograph at higher resolution. It clearly shows the formation of line structures of indium having periodicity 9 μm with width of 3 μm on the target. Optical microscopic

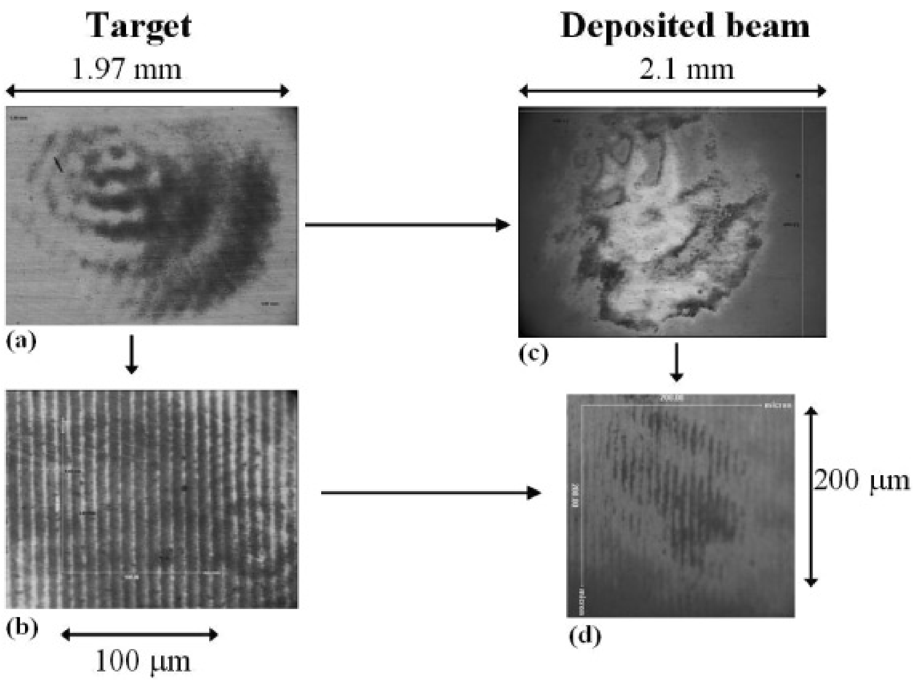

Fig. 3. Optical micrograph of target and deposited one-dimensional arrays of atomic beams obtained by illumination with two beam interference pattern.

images of the corresponding glass substrate obtained by deposition of six consecutive shots of pulsed atomic beams are shown in Figures 3c and 3d. Figure 3c shows the complete deposition of material emitted from the target thin film and Figure 3d shows the corresponding periodic structure at higher resolution. It shows the periodic line pattern with periodicity 10.2 μm and deposited line width 8.2 μm similar to that of the target, Figure 3b. This confirms that the sculpting of the atomic beam in one dimension can be performed by interference pattern for the generation of large number of parallel pulsed atomic beams in a single shot. The overall size of the system of atomic beams as well as the periodicity of the deposited beam onto the substrate (Figs. 3c and 3d) is slightly more than that of the material ablated from the target (Figs. 3a and 3b). This is because of divergence of atomic beam generated by ablation of the material via rear side illumination.

After successfully sculpting the atomic beam in one dimension, we have conducted experiment for sculpting the atomic beam in two dimensions to generate the discrete atomic beams arranged in a square geometry. This serves as a matrix of micro-ovens. To obtain the multiple periodic atomic beams in two dimensions, the interference pattern also has to be periodic in two dimensions. Therefore, thin film of indium was ablated with single shot of four beams interference pattern of Figure 2. The laser fluence at the target in this case was around 270 mJ/cm^2. The target thin film and the deposited atomic beam on the glass substrate were scanned using atomic force microscope. Figures 4a and 4b show AFM scan images of target indium thin film in two- and three-dimensional view, respectively. Height profile of these images along the line AB and CD are shown in Figures 4c and 4d, respectively. These images clearly show formation of nano sized periodic holes and hillocks of indium on the thin film having periodicity 593 nm and FWHM of a hole equal to 263 nm. This confirms the periodic ablation of thin film in two dimensions. Figures 5a and 5b shows the AFM scans of deposited atomic beam obtained by depositing five consecutive shots of the sculpted beam (Fig. 2) in two- and three-dimensional view, respectively. Height profile of these images along the line AB is shown in Figure 5c. These images show the nano-sized dots on the substrate with periodicity 630 nm and FWHM equal to 294 nm, confirming the production of arrays of multiple atomic beams having bi-directional periodicity.

CONCLUSION

We have generated periodic arrays of atomic beams in one dimension as well as two dimensions via rear side ablation of indium thin film by high power two and four beams laser interference pattern at relatively low fluence. Micrograph images and AFM scan pictures confirms the formation of sculpted one- and two-dimensional arrays of atomic beams having periodicity ranging from 10 μm to the 630 nm with size of the individual beams ranging from 8.2 μm to 294 nm. The periodicity and the size of individual beam depend on the spatial frequency of the interference pattern and the beam energy, respectively.

The advantages of rear side selective laser ablation of thin film reported in this paper are three fold.

1. Selective laser ablation lithography:
   First the target used for ablation gets imprinted with periodic micro-nanoscopic information of light beams via ablation by two and four beam interference pat-

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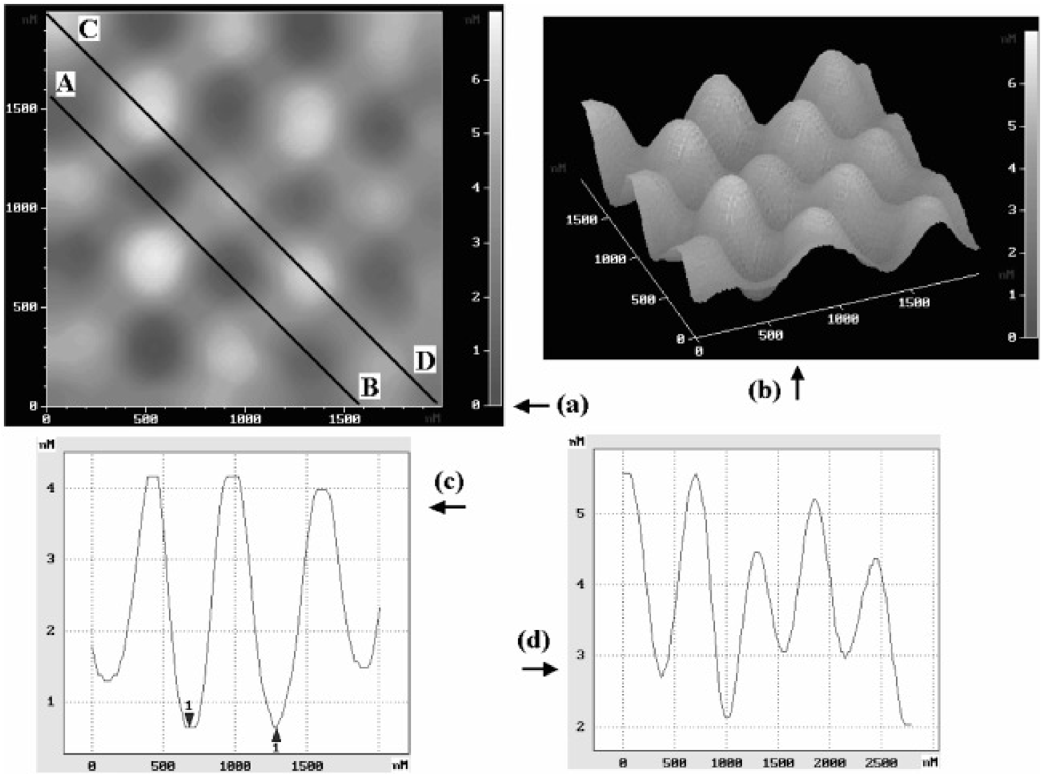

Fig. 4. AFM scan pictures (unit nm) of target after illumination with a single shot of four beams interference pattern. (**a**) Two-dimensional view. (**b**) Three-dimensional view. (**c**) Oscilloscope traces along line AB. (**d**) Oscilloscope trace along line CD.

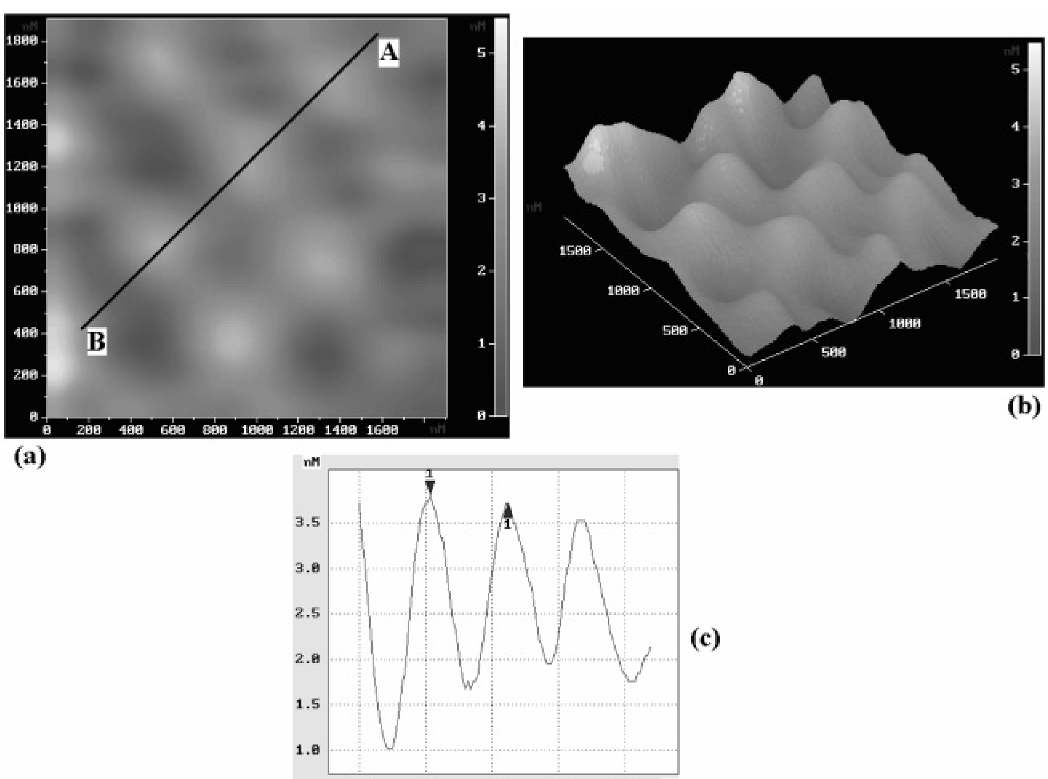

Fig. 5. AFM scan pictures (unit nm) of deposited sculpted square arrays of atomic beams. (**a**) Two-dimensional view. (**b**) Three-dimensional view. (**c**) Oscilloscope trace along line AB.

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tern. So this part itself acts as a single-step single-shot lithographic technique without using any mask.

2. Multiple atomic beams for atom lithography using dipole force:
   Second, the ablated material from above results in the generation of the multiple atomic beam which can be focus down with the help of TEM_{00} mode of laser, acting as an atomic lens, for obtaining structures with periodicities less than $\lambda/2$ by atom lithography using dipole force (Khare *et al*., 2004; Alti & Khare, 2006*b*).
3. Multiple atomic beams for direct lithography:
   Third, the multiple atomic beams deposited directly onto the substrate serves as micro-nano fabrication of periodic structure.

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