Atomic nanofabrication using an ytterbium atomic beam

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Abstract

Highly parallel and periodically narrow lines of ytterbium (Yb) atoms were successfully produced on a substrate using a near resonant laser light and direct-write atomic nanofabrication. Yb atoms are a promising material for nanofabrication using atom optics particularly due to their electric conductivity, the laser wavelength required for their manipulation, and the vapor pressure required for their fabrication. Collimated $^{174}$Yb atoms were channeled into the nodes of an optical standing wave with dipole force and then deposited onto a substrate. We clearly observed a grating pattern of Yb atoms fabricated on a substrate with a line separation of approximately 200 nm after examining the surface of the substrate with an atomic force microscope. This is the first demonstration of nanofabrication using the atom-optical approach with Yb atoms.

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1. Introduction

The recent progress in laser cooling and trapping of atoms has opened a new door to atom optics. One of the most promising applications of this field is direct-write nanofabrication based on the precise handling of atoms using laser light. This technique is called atomic nanofabrication (AN). Compared with conventional lithography methods, AN has potentially the various attractive advantages in performance [1]. We investigated an atomic beam guide [2] and high-resolution atomic channeling [3] to realize new AN methods that perform much better at producing atomic patterns. AN, however, currently faces some problems. Primarily, deposition using this method has never been demonstrated with atomic species other than Na [4], Cr [5–7], and Al [8]. Therefore, expanding the atomic species for use with AN has great practical significance.

In this paper, we describe an experiment where ytterbium (Yb) atoms were deposited on a nanometer scale by atom-optical manipulation for the first time. Yb atoms are a promising material for this nanofabrication technique. A 399-nm radiation for manipulating Yb atoms is obtained from a frequency-doubled Ti:Sapphire laser or an ultraviolet laser diode. We can produce the nanostructures using a thermal Yb beam at an oven temperature of almost 1000 K. This eliminates the need for special vacuum chamber equipment and it also prevents the emission of impurity gases at higher oven temperatures. The deposited structures of the Yb atoms can be examined with a variety of microscopic techniques. We can potentially take advantage of various precise manipulation methods of Yb atoms [9–15] and even use the Bose–Einstein condensation of Yb atoms [16] for engineering applications. Following the typical AN procedure, the collimated $^{174}$Yb atoms were focused to lines separated by half of the wavelength onto a substrate using nano-lens arrays for atoms made of the intense optical standing wave (SW). We successfully produced a nanograting structure of the Yb atoms. The properties of the obtained pattern were measured with an atomic force microscope (AFM). We discuss the effect of atom beam divergence on the deposited line width of the Yb atoms. Furthermore, we propose a new AN scheme based on
the far-off resonant trapping (FORT) of atoms to produce an atomic pattern whose period is not restricted to the resonant wavelength of atoms.

2. Experimental

The optical transition from the ground ($^1S_0$) to an excited ($^1P_1$) state of the Yb atom was used for the atomic manipulation. This transition has a natural line width of $\Gamma = 2\pi \times 28$ MHz and a saturation intensity of 50 mW/cm$^2$. Two sets of frequency-doubled cw single-mode Ti:sapphire lasers, pumped by an Ar$^+$-ion laser, were used to generate the 399-nm radiation. One was used for optical molasses (OM) and the other for the generation of SW. The Yb atom has seven stable isotopes. We chose $^{174}$Yb for our experiments because it exists in the largest abundance (31.7%). A schematic diagram of our experimental setup is shown in Fig. 1. The transverse collimation of the Yb beam was set to be 4 mrad with two pinholes. The oven was maintained at a temperature of 1100 K during the deposition process. The $^{174}$Yb atoms in the thermal beam were transversely cooled with the OM at 10 cm downstream from the second pinhole. The optical power of each 399-nm radiation at the OM was 30 mW, apertured to a rectangular shape 4 mm high and 15 mm along the atomic beam. The laser frequency was detuned 14 MHz to the red of the $^{174}$Yb: $^1S_0-^1P_1$ resonance. The laser beam for forming the SW, nominally Gaussian in profile, was focused such that its waist location coincided with the SW mirror. The waist size of the laser beam at the SW mirror was approximately 0.5 mm in our experiment, and the intensity of the SW light field amounted to 40 W/cm$^2$. Shortly after the SW, we mounted the silicon substrate, which is perpendicular to the SW mirror. The detuning of the laser frequency was set 1.5 GHz above the $^{174}$Yb: $^1S_0-^1P_1$ resonance.

3. Results and discussion

We first checked the divergence of the $^{174}$Yb beam after the OM. A probe beam that was resonant with the $^{174}$Yb: $^1S_0-^1P_1$ transition was intersected at a right angle at a position 80 cm downstream from the OM. From the CCD pictures taken with a highly sensitive camera we determined the atom beam diameter at the probe area and deduced the beam divergence. As a result, the divergence was improved to 1.5 mrad due to the Doppler cooling in transverse direction in the OM area. We calculated the maximum trappable velocity of a $^{174}$Yb atom with an optical SW to be 0.48 m/s under our experimental conditions, which means that more than 90% of the $^{174}$Yb atoms in our collimated beam could be captured by the prepared potential hills.

Next, we focused the collimated $^{174}$Yb atoms using an array of atom-optical lenses in the SW region. We set the deposition time to be 30 min. Fig. 2 shows the observed AFM images of the deposited Yb gratings analyzed with the AFM. Fig. 2(a) is a 10-μm scan that clearly shows a regular and highly parallel array of Yb lines. Fig. 2(b) indicates the averaged line profile of the AFM data along the Yb lines, covering a 3-μm distance. From these results, the spacing between the lines was determined to be 205 ± 9 nm, and this value predictably coincided with the wavelength of the optical SW (199.5 nm) within the error margin. The Yb features maintained their integrity when removed from

![Fig. 1. Schematic diagram of the experimental setup. SW denotes the optical standing wave. SHG represents the efficient second harmonic generation using an LBO crystal and an external enhancement cavity.](image-url)
the vacuum chamber. Our measurements also showed that the typical height of the features was 10 nm and the line width (FWHM) 93 ± 5 nm.

To estimate the narrowest achievable line width, we modeled the channeling process. We traced 400,000 atomic trajectories without the effect of spontaneous emission under our experimental parameters. The predicted atomic pattern is indicated in Fig. 3(a). We can expect an FWHM of 56 nm for line width is attainable even under these experimental conditions. The discrepancy between the simulated and the experimental result can be attributed to a number of factors including the diffusion of Yb atoms on the substrate during the deposition, the fluctuation in SW laser power and frequency, and mechanical vibrations of the substrate. The beam divergence of an atomic source plays a particularly significant role in narrowing the expected line width [17]. The estimated atomic pattern when the transverse kinetic energy of atoms is cooled down to the Doppler limit for the Yb:1S0–1P1 transition (1.1 mrad) is illustrated in Fig. 3(b). The line width is reduced to 42 nm in this case. Fig. 3(c) illustrates the predicted atomic pattern if the atom beam is transversely cooled down to 0.2 mrad. The line width is expected to be further reduced to 20 nm even though the Yb beam has a broad thermal velocity distribution. For producing such a highly collimated atom beam, applying the intercombination MOT [13] to transverse cooling of the Yb beam should be effective. The beam divergence, which is restricted by the extremely narrow natural line width of the Yb:1S0–3P1 transition, should reach about 0.1 mrad.

At present, the period of an atomic pattern is limited by the resonant wavelength of the atomic transition. We propose a new scheme based on FORT to solve this problem. We use a laser beam that has a frequency far from the atomic resonance instead of nearly resonant light to generate the SW as a light mask. We simulated the predicted Yb atomic pattern using this far-off resonant light mask. We assumed that the thermal 174Yb atom beam with a divergence of 1.5 mrad was channeled with an optical SW composed of a 532-nm single-mode radiation and a 10 W power. The beam diameter (d) of SW was set to be 20 or 100 µm in our calculations. The simulated results are indicated in Fig. 4. The solid line shows the predicted atomic pattern for d=20 µm, and the dotted line for d=100 µm. The periodic grating structures of the Yb atoms were also expected under these conditions. The spacing of the atomic lines was determined to be 266 nm as expected, which coincides with the wavelength of the employed SW and differs strongly from that given by the resonant wavelength of Yb atoms (199.5 nm) as described above. The contrast of the predicted patterns in Fig. 4 became worse than those in Fig. 3(a)–(c). We think that the main reason for this is the extremely short length of interaction for d=20 µm and the insufficient dipole force.
potential height for capturing atoms with $d = 100 \, \mu m$. The FORT of Yb atoms has already been demonstrated [15]. A diode-pumped, frequency-doubled Nd:YVO$_4$ laser system, which is commercially available, may be employed as a light source for generating a far-off resonant light mask. Therefore, our proposed scheme is thought to be feasible, and we should be able to deposit an atomic pattern with an arbitrary period by developing this experimental scheme.

4. Conclusions

We described the first demonstration of a direct optical deposition of $^{174}$Yb atoms onto a substrate with light mask patterning. An Yb beam was successfully collimated, focused, and deposited onto a substrate using a 399-nm radiation beam. We investigated the properties in the atomic structure using AFM and we clearly observed a parallel well-ordered array of nanometer-scale lines composed of Yb atoms covering a macroscopic area. The observed pitch was determined to be $205 \pm 9 \, \text{nm}$ and the line width was $93 \pm 5 \, \text{nm}$. A simulation of the atomic trajectories in an optical SW revealed that the line width of the features would be significantly improved by decreasing the kinetic energy of $^{174}$Yb atoms in transverse direction. We also proposed a new AN scheme based on FORT, which will enable producing an atomic pattern with a period far from the atomic resonance wavelength, even with an arbitrary period.

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Fig. 4. Predicted patterns of Yb atoms using the far-off resonant light mask ($\lambda = 532 \, \text{nm}, 10 \, \text{W}$). The horizontal axis indicates the relative position to the antinode of the optical standing wave (SW). The solid and the dotted lines represent the simulated results with a SW beam diameter for of 20 and $100 \, \mu m$, respectively.
