The influence of divergence angle on the deposition of neutral chromium atoms using a laser standing wave*

Zhang Wen-Tao(张文涛)[a)†], Zhu Bao-Hua(朱保华)[a)], Huang Jing(黄 静)[b)], Xiong Xian-Ming(熊显名)[a)], and Jiang Qu-Bo(蒋曲博)[a)]

[a)] *Guilin University of Electronic Technology, Guilin* 541004, *China*

[b)] *Guizhou University for Nationalities, Guiyang* 550000, *China*

(Received 21 June 2011; revised manuscript received 11 October 2011)

The characteristics of neutral chromium atoms in the standing wave field are discussed. Based on a semi-classical model, the motion equation of neutral atoms in the laser standing wave field is analyzed, and the trajectories of the atoms are obtained by simulations with the different divergence angles of the atomic beam. The simulation results show that the full width at half maximum (FWHM) of the stripe is 2.75 nm and the contrast is 38.5 : 1 when the divergence angle equals 0 mrad, the FWHM is 24.1 nm and the contrast is 6.8:1 when the divergence angle equals 0.2 mrad and the FWHMs are 58.6 and 137.8 nm, and the contrasts are 3.3 : 1 and 1.6 : 1 when the divergence angles equal 0.5 and 1.0 mrad, respectively.

Keywords: atom lithography, laser standing wave, full wave at half maximum, contrast

PACS: 33.80.–b, 42.50.Wk **DOI:** 10.1088/1674-1056/21/3/033301

1. Introduction

The remarkable capabilities of laser cooling and trapping techniques for the precise control of atoms have led to great advances in the field of atom optics. Direct-write atom lithography is one of the most promising methods to fabricate nanometer-scale features. Using neutral atoms for nanofabrication has a number of distinct advantages over the other methods, including photon, electron and ion beam lithography. Because the neutral atoms are massive compared with the photons or the electrons, they tend to have a very small de Broglie wavelength, and hence the diffraction effects do not affect the resolution limit. Also, because they are charge-neutral, unlike electrons or ions, neutral atoms are not affected by the space charge effect, which makes it easy to concentrate many particles into a very small region.[1−3] The basic principle of atom lithography relies on the concentration of the atomic flux in space by using spatially modulated atom–light interactions. In atom lithography schemes, a standing wave (SW) of light that serves as an array of parallel atom lenses is used to concentrate the atomic flux periodically and create desired patterns at the nanometer scale.[4] Up until now, atom lithography has been applied using different atoms including sodium,[5] chromium,[4] aluminum,[6] cesium,[7] barium[8] and ytterbium.[9]

The purpose of direct-write atomic lithography is to deposit small features. There are some effects that contribute to the broadening of the features, such as the divergence angle of the atomic beam, the distribution of the longitudinal velocities of atoms, and the chromatic and spherical aberration. The structural width deteriorates quickly with the increasing divergence angle of the atomic beam. The SW optical potential is extremely shallow, so the atomic velocities along the SW direction must be low for the atoms to be trapped in the SW nodes (antinodes). Between these two reasons, the divergence angle of the atomic beam has the stronger effect on the nanometer scale features. In this paper, the deposition of nanometer-scale features using neutral chromium atoms as the working particles is studied based on a semi-classical model.

2. Semi-classical model

There are two different types of interactions that can be used to manipulate neutral chromium atoms. The dissipative force can be used to collimate the atomic beam, and the dipole force can be used to fo-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11064002 and 11061011).

†Corresponding author. E-mail: glietzwt@163.com

© 2012 Chinese Physical Society and IOP Publishing Ltd

cus the atoms. The standing wave field acts like an array of cylindrical lenses and can focus atoms onto the substrate. The atoms then form the nanometer structures. In a standing wave field, a dipole moment can be induced in the neutral chromium atoms and can be resonantly enhanced by tuning the oscillation frequency close to the neutral chromium atomic resonance. The coupling between the induced dipole moment and the electric field leads to a spatially dependent optical potential that exerts a force on the neutral chromium atom. In the case of a large detuning, the dipole force is proportional to the intensity of the electromagnetic field at the position of the neutral atom. Depending on the detuning of the laser frequency with respect to the resonance frequency, the neutral chromium atom feels a force towards high or low intensity regions. For the neutral chromium atoms, the standing wave field acts like an array of cylindrical lenses and can focus them onto the substrate. The light intensity distribution of the SW laser field can be expressed as[10]

$$I(x,z) = I_{\max}\,\mathrm{e}^{-2z^2/\omega_{\mathrm{o}}^2}\sin^2(kx), \tag{1}$$

where $I_{\max}$ is the maximal light intensity, ω_{o} is the beam waist width, and k is the wave vector. If the atomic–optical system reaches the steady state, the potential of the SW laser field that the atoms experience takes the form[11]

$$U(x,y,z) = \frac{\hbar\Delta}{2}\ln[1+p(x,y,z)], \tag{2}$$

where

$$p(x,y,z) = \frac{I(x,y,z)}{I_{\mathrm{s}}}\frac{\Gamma^2}{\Gamma^2+4\Delta^2} = p_{\mathrm{o}}G(x,y,z),$$
$$p_{\mathrm{o}} = \frac{I_{\mathrm{o}}}{I_{\mathrm{s}}}\frac{\Gamma^2}{\Gamma^2+4\Delta^2}$$

is the saturated parameter, $\Delta = \omega_{\mathrm{L}} - \omega_{\mathrm{o}}$, Γ and I_{s} are the detuning, the line width and the saturated intensity, respectively. For the chromium atom, $\Gamma = 5$ MHz, $I_{\mathrm{s}} = 85$ W/m^2. In the Gaussian SW laser field, $G(x,z) = \exp(-2Z^2)\sin^2(kx)$, where $Z = z/\omega_{\mathrm{o}}$. In the following simulation, we take $\omega_{\mathrm{o}} = 100$ μm, $\Delta = 200$ MHz, and $k = 2\pi/425$ nm.

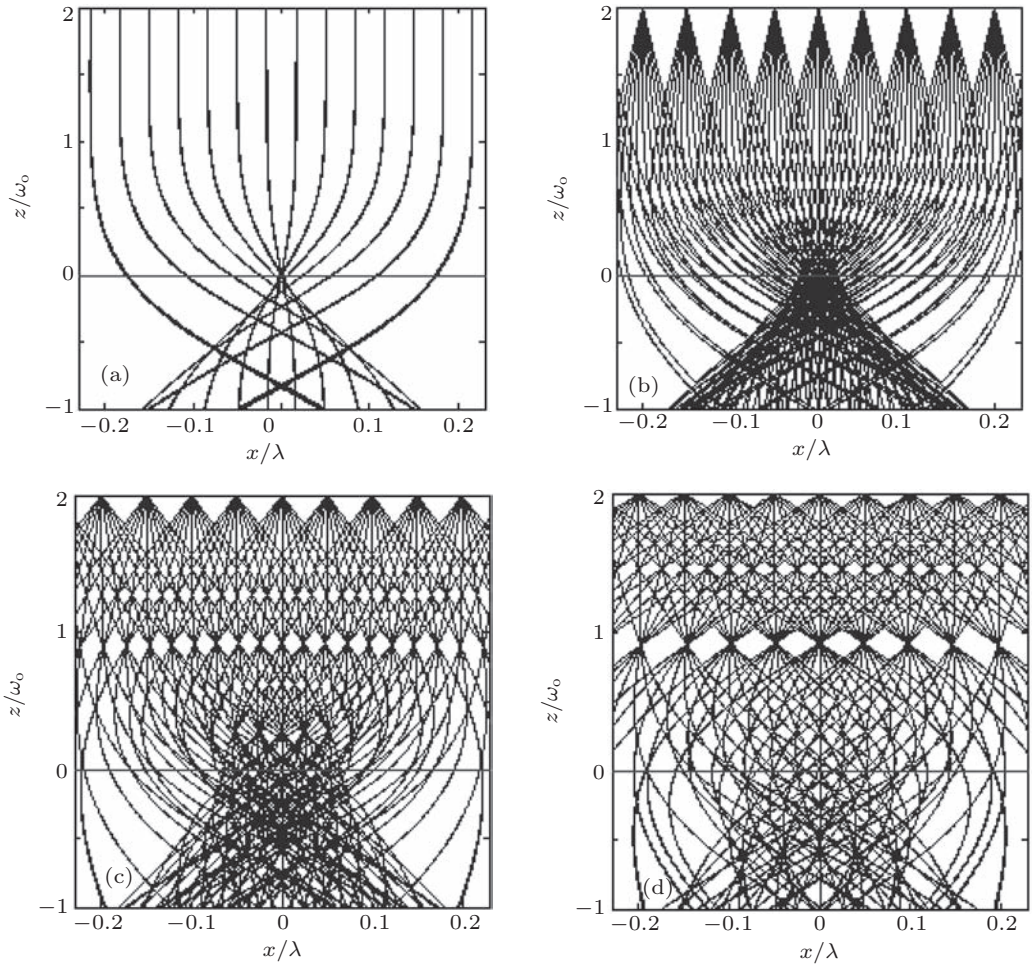


Fig. 1. The trajectories of chromium atoms in the laser standing wave field when the divergence angles of the atomic beam are (a) 0, (b) 0.2, (c) 0.5 and (d) 1.0 mrad.

The force acting on the chromium atoms can be derived from formula (2) as

$$F(x,t) = -\frac{\partial U(x,t)}{\partial x}. \tag{3}$$

By solving the motion equation[12]

$$m\frac{\mathrm{d}^2x}{\mathrm{d}t^2} = F(x,t), \tag{4}$$

the trajectory of the chromium atom in the laser standing wave field can be obtained. In order to express the atomic trajectory, we introduce parameter $a = (\eta\Delta/2E_\mathrm{o})p_\mathrm{o}k^2\omega_\mathrm{o}^2$, where $\eta = 1$ is the quantum efficiency, and E_o is the energy of the atom. The above expression contains all the information about the SW laser field, so the trajectories of the moving chromium atoms can be described by changing the parameter. The semi-classical atomic trajectory is calculated by employing the adaptive step size fourth-order Adams–Moulton type algorithm. Figure 1 shows the trajectories of the chromium atoms in the laser standing wave field with different divergence angles of the atomic beam. In Fig. 1(a), the divergence angle of the atomic beam is 0 mrad, and it is shown that under this condition the atom has no transverse velocity component. The divergence angles of the atomic beam are 0.2, 0.5 and 1.0 mrad in Figs. 1(b), 1(c) and 1(d), respectively. From the figure, we can see that the deposition region widens as the divergence angle of the atomic beam increases.

3. The deposition characteristics of Cr atoms

From formulae (3) and (4), the final position of the chromium atom when it passes through the standing wave can be calculated by using the four-order Runge–Kutta algorithm, and the deposition characteristics can be obtained by using the accumulative algorithm. By tracing 64000 chromium atomic trajectories, the deposition characteristics can be obtained. Figure 2 shows the characteristics of the deposition of the chromium atom with different divergence angles of the atomic beam. It can be seen that with the increase in the divergence angle of the atomic beam, the quality of the deposited structure decreases. This means that the deposition stripe will be widened and the height of deposition will be decreased as the divergence angle of the atomic beam increases.

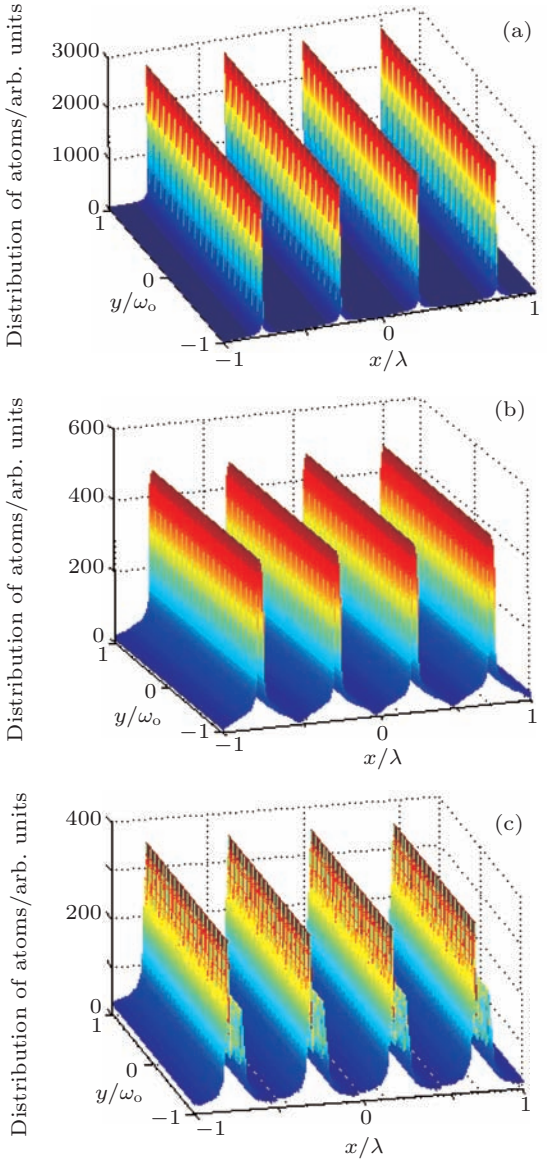


Fig. 2. (colour online) The deposition characteristics when the divergence angles of the atomic beam are (a) 0, (b) 0.2, (c) 0.5 and (d) 1.0 mrad.

In order to describe the characteristics of the nano feature, two parameters are defined, i.e. contrast H and full width at half maximum (FWHM). The FWHM is a simple and well defined number, which can be used to compare the quality of the deposition. The contrast is defined by $H = h_1/h_2$, with h_1 and h_2 being the heights of the feature and the fundus of the deposition stripe, respectively. For a larger H and a smaller FWHM, the quality of the deposition is more acceptable. Figure 3 shows the characteristics of H and FWHM with different divergence angles of the chromium atomic beam. From Fig. 3, it can be seen that when the divergence angle equals 0 mrad, the chromium atomic beam has no transverse velocity component, the FWHM of the deposition stripe is 2.75 nm, and H is 38.5:1. When the divergence angle

of the chromium atomic beam is 0.2 mrad, the FWHM of the deposition stripe is 24.1 nm and H is 6.8:1. When the divergence angle is 0.5 mrad, the FWHM equals 58.6 nm and H is equal to 3.3:1. The FWHM is 137.8 nm and H is 1.6:1 when the divergence angle of the chromium atomic beam equals 1.0 mrad. From Fig. 3, it can be seen that the effect of atomic beam divergence is very strong on the deposition stripe characteristics, and at the same time, when the divergence is below 0.5 mrad, the FWHM and H of the stripe are acceptable. So in order to get high-quality nano structures using atom lithography, the divergence of the atomic beam must be compressed to some extent.

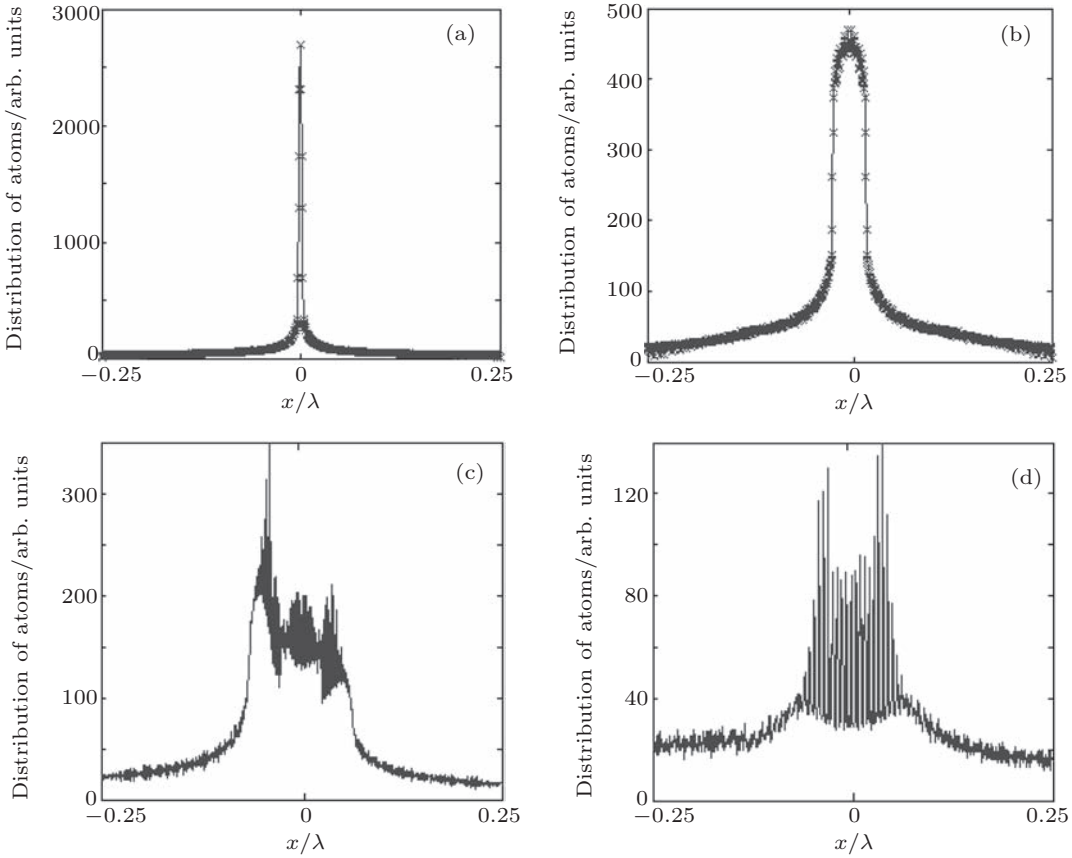


Fig. 3. The distributions of atoms when the divergence angles of the atomic beam are (a) 0, (b) 0.2, (c) 0.5 and (d) 1.0 mrad.

4. Conclusion

Divergence angle plays a crucial role in determining deposition nano features, so the preparation of a highly collimated and transversely cooled atomic beam with a divergence angle less than 0.5 mrad is essential to minimize the severe disadvantages in the deposition of atoms.

References

[1] McClelland J J, Scholten R E and Palm E C 1993 *Science* **262** 877

[2] Arun R, Cohen O and Averbukh I S 2010 *Phys. Rev.* A **81** 063808

[3] McClelland J J 1995 *J. Opt. Soc. Am.* B **12** 1761

[4] Anderson W R, Brandley C C, McClelland J J and Celotta R J 1999 *Phys. Rev.* A **59** 2476

[5] Prentiss M, Timp G and Bigelow N 1992 *Appl. Phys. Lett.* **60** 1027

[6] McGowan R W, Giltner D M and Lee S A 1995 *Opt. Lett.* **20** 2535

[7] Camposeo A, Cervelli F and Tantussi F 2003 *Materials Science and Engineering* C **23** 1087

[8] Fioretti A, Camposeo A and Tantussi F 2005 *Appl. Surf. Sci.* **248** 196

[9] Ohmukai R, Urabe S and Watanabe M 2003 *Appl. Phys* B **77** 415

[10] Ma B, Ma Y, Zhao M, Ma S S and Wang Z S 2006 *Acta Phys. Sin.* **55** 668 (in Chinese)

[11] Zhang W T, Zhu B H and Xiong X M 2009 *Acta Phys. Sin.* **58** 8199 (in Chinese)

[12] Zhang W T, Zhu B H, Xiong X M and Huang J 2011 *Acta Phys. Sin.* **60** 063202 (in Chinese)