Fabrication of complex nanostructures based on laser manipulation of atoms

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Atom lithography suffers from serious practical limitations, which have limited the application of this technique in practice. Double deposition method, manipulation of atoms with a linear polarization gradient laser field and moving substrate during deposition process to fabricate nanostructure with a period less than half an optical wavelength, was discussed. The atomic density distribution transversal to the beam direction closely mimics the light intensity pattern, and the structures are equally complex as the inducing light intensity. The variety of patterns and the role of the different parameters were discussed. The optical focusing of group III atoms provides a new approach for controlling the spatial composition of atoms during the growth of III-V heterostructures.

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The freedom of an atomic beam can be controlled to nanometer scale by laser manipulation, which has opened a way to fabricate nanostructures based on laser cooling and trapping. Atom lithography has seen rapid development in the last decade[1−9]. Up to now, the generation of lines[3−8] with period half laser wavelength near an atomic resonance has been reported for sodium, chromium, aluminum, and cesium. For chromium, various two-dimensional (2D) structures with a period of 1/2 wavelength or 2/3 wavelengths have also been achieved. Atom lithography offers advantages beyond a small fundamental limit on feature size. In comparison with alternatives like electron beam, ion beam or X-ray lithography, there are no electrostatic interactions within a neutral beam that limit focusing or flux density, either in a single beam or in a parallel array of beams[5−9]. Furthermore, the relatively low thermal speed of the atoms does not cause any surface damage, unlike X-rays and charged particles.

As a new technology, atom lithography suffers from serious practical limitations, which have limited the application of this technique in practice. To date, only very simple patterns have been demonstrated and a few atomic species have been successfully manipulated due to the difficulty of this technique. Fabrication of high-density nanostructures and complex nanostructures is a hot topic in atom lithography. Double deposition method, manipulation of atoms with a linear polarization gradient laser field and moving substrate during deposition process to fabricate nanostructure with a period less than half an optical wavelength, was discussed. Several methods to fabricate 2D and 3D structures were given.

The structure period of $\lambda/2$ can be beaten by changing the detuning of the standing wave field from blue to red halfway through the deposition time. We use semi-classical model[1,2] to simulate double deposition process. Since the lines are formed at the light intensity minima for positive and at the light intensity maxima for negative detuning, and a detuning switch corresponds to moving the light mask by half the period (see Fig. 1). Dashed line, dotted line and solid line stand for positive detuning, negative detuning and a double deposition, respectively. Triangle is the detuning between laser frequency and the atomic transition frequency. This leads to a line structure with a period of $\lambda/4$. From the simulation result shown in Fig.1 we can see that the structure period is $\lambda/4$, but the feature contrast is decreased because of a double deposition[2].

The dipole forces also appear in light fields of uniform overall intensity in the presence of polarization gradients, as a result of the magnetic substructure of the atomic transition. The "lin ⊥ lin" configuration polarization gradient field can be viewed as two standing waves of σ^+ and σ^- polarization, respectively. When an atom with a magnetic substructure in its quasi-resonant dipole transition is placed into this light field, the induced dipole interaction is governed by the conservation of angular momentum. As a result, the peak-to-peak distance of $\lambda/8$ will appear.

Due to the influence of velocity spread, beam spread, wave nature of atoms and so on, aberrations exist in atom lens generated by a laser standing wave. For initial transversal position far away from the axis paraxial approximation begins to fail, these atoms are not well focused as a result of spherical aberration. To solve this problem, the combination of absorption mask and physical mask can be used in experimental setup to eliminate the background. An aperture can be used to block the portion of atomic beam that does not enter regions close to potential minima. As illustrated in the Fig. 2, the background is virtually absent and the features are much sharper when a mechanical mask is used. Moving the substrate in steps that is a fraction of the size of the

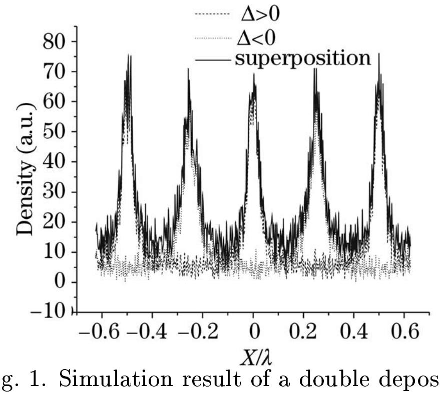

Fig. 1. Simulation result of a double deposition.

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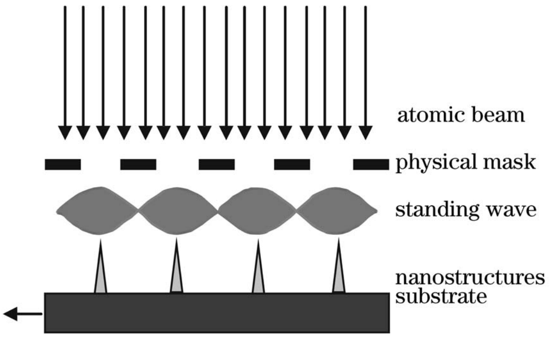

Fig. 2. Moving substrate during deposition process.

standing wave period can further decrease the separation between features, which will increase the density of nanostructures. But the separation is limited by the minimum feature size.

In optical lithography, light passes through masks to project an image onto the substrate. The roles of light and matter in atom lithography are interchanged, in which atoms are sent through a regions of gradient laser field, and the light intensity distribution is transformed into the atomic image on the substrate. The atomic density distribution along transversal direction closely mimics the light intensity pattern. In principle, it is possible to create structures that are equally complex as the light intensity pattern. Conservative dipole forces derive from the gradient of the laser field, which are used for steering atoms into the desired patterns in atom lithography. Once the light field intensity distribution is known, atomic density distribution on the substrate can be calculated by Monte-Carlo scheme and trajectory tracing method. Disregarding the influence of polarization, any intensity distribution is generated from a superposition of light waves. Figure 3(a) shows an example of intensity distribution created by the superposition of 25 laser beams with randomly generated directions in a plane. Figure 3(b) is the contour and the distribution of dipole force, and all parameters entering this simulation are the same as those in Fig. 3(a). Each laser beam with a new direction adds a new degree of freedom to the pattern formed by the light field. Figure 4 shows intensity distributions created by the superposition of 4 laser beams with different direction distributions. How complex the structures to be generated with light intensity may be, and what types of structures can be generated remains an open question.

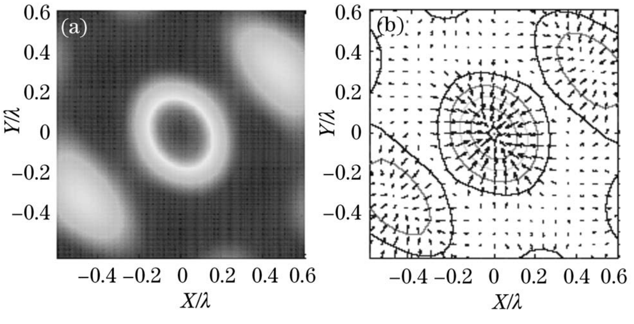

Fig. 3. Light intensity distribution and dipole force distribution.

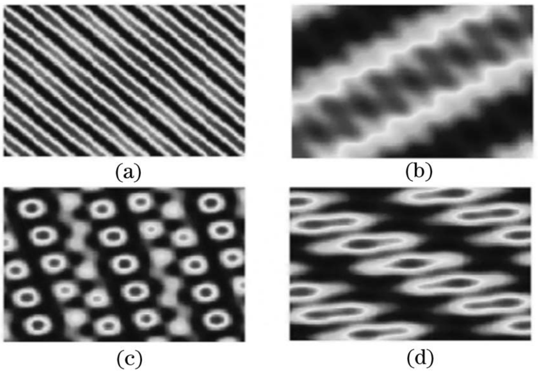

Fig. 4. The variety of patterns created by the superposition of four laser beams with different direction distributions.

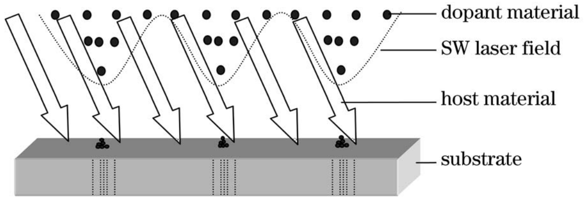

Fig. 5. Sketch of the principle of structured doping with light forces. Only dopant material can be controlled by laser beam.

The group III atoms are the key building blocks of modern III-V semiconductor diode lasers, and the ability to directly focus Ga and In offers new opportunities for the fabrication of ultralow-threshold quantum wire and quantum dot lasers. The optical focusing of group III atoms provides a new approach for controlling the spatial composition of atoms during the growth of III-V heterostructures. The laser beam for focusing can be introduced into a MBE chamber directly in front of the substrate. Figure 5 is the sketch of flux control of the different components. If the focusing laser is chopped on and off during growth, a composition-modulated heterostructure could be created. Utilizing specific properties of atom manipulation with light, one can change the lateral pattern by switching the intensities, frequencies or polarizations of the laser beams constituting the light field.

In conclusion, we discussed the methods on how to fabricate complex nanostructures based on laser manipulation of atoms, which will serve as a fruitful guide in performing the laser-focused atomic deposition in our laboratory.

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References

1. X. Z. Chen, H. M. Yao, and X. N. Chen, Chin. Opt. Lett. **2,** 187 (2004).

2. X. Z. Chen, H. M. Yao, and X. N. Chen, Modern Phys. Lett. B **18,** 233 (2004).
3. J. J. McCelland, R. E. Scholten, E. C. Palm, and R. J. Celotta, Science **162,** 877 (1993).
4. W. R. Anderson, C. C. Bradley, J. J. McCelland, and R. J. Celotta, Phys. Review A **59,** 2476 (1999).
5. J. J. McClelland, J. Optical Society of America B **12,** 1761 (1995).
6. R. W. McGowan, D. M. Giltner, and S. A. Lee, Opt. Lett. **20,** 2535 (1995).
7. F. Lison, D. Haubrich, P. Schuh, and D. Meschede, Appl. Phys. B **65,**419 (1997).
8. M. K. Olsen, T. Wong, S. M. Tan, and D. F. Walls, Phys. Rev. A **59,** 3358 (1996).
9. D. Meschede, and H. Metcalf, J. Phys. D: Appl. Phys. **36,** R17 (2003).