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Fabrication of nano-structural arrays by channeling pulsed atomic beams through an intensity-modulated optical standing wave with a time-varying atom focal length

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Abstract

We show that it is feasible to produce one- and two-dimensional nano-structure arrays by passing a pulsed atomic beam through an intensity-modulated continuous-wave (cw) laser standing wave that has a time-varying atom focal length and thus achieves the effect of "cooling" along the longitudinal direction. This enables fabrication of vertically heterogeneous nano-structures with single-wavelength laser standing wave(s). © 2002 Elsevier Science B.V. All rights reserved.

In recent years, new forms of materials, made from conventional ones but reduced in one dimension (1-D) (i.e., thin films) or two dimensions (2-D) (i.e., thin wires) or even three dimensions (3-D) (i.e., dots or particles), have drawn considerable attention in both material research community and industry. In particular, nano-particles that are confined in all three dimensions have unique (mesoscopic) electronic properties and in turn optical and magnetic properties that differ from those of their bulk (macroscopic) or atomic (microscopic) counterparts.

Timp and coworkers and others demonstrated a scheme for nanometer-scale lithography by channeling a thermally produced continuous-wave (cw) atom beam through a laser standing wave [1–11]. To reduce the smearing effect of the transverse velocity spread in the atomic beam, the beam has to be optically cooled in transverse direction before passing through the standing wave [1–3]. For optical cooling to be effective, the frequency of the cooling laser ω has to be tuned to a suitable transition frequency ω_0 of the atoms in the beam within 100 MHz. The frequency of the standing wave laser is also within a few hundred MHz from ω_0. Implementation of such a technique thus depends on the detail atomic spectral information and suitable cw lasers whose frequencies are within a few GHz or a few hundred MHz from a usable atomic transition. As a result this spectral dependence makes it almost impossible to fabricate vertically hetero-structured nano-arrays that are made of different elemental materials. Furthermore, because the focal length for a thermal atom

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by a laser standing wave is dependent on the longitudinal velocity of the atom and the Maxwellian velocity spread is not compensated for, this method suffers from ''chromatic aberration'' and can thus only produce nano-structures with a full-width-half-max of 30 nm or larger [11].

We propose a new scheme of using laser standing waves to fabricate nano-structure arrays that (1) is independent of the spectral specifics of atoms, and (2) provides an effective cooling in the longitudinal direction. This is achieved by channeling a laser-ablation produced pulsed atomic beam through a synchronously modulated cw laser standing wave at off-resonance condition. By operating at an off-resonance condition, we remove the spectral dependence of this nano-fabrication method so that *one* cw laser system can be used to produce the same type of nano-structural array from different elemental materials and thus enables fabrication of vertically heterogeneous nanostructure arrays. By using a synchronously modulated cw laser standing wave, we can so adjust the temporal profile of the standing wave intensity that the focal length for a fast atom with an early and yet well-specified arrival time is made the same as that for a slow atom with a late arrival time. This *effectively* achieves the longitudinal cooling that is not possible with the conventional cw atom optics.

The proposed experimental setup is shown in Fig. 1. A pulsed atomic beam is produced by laser-ablation of a material target with a nanosecond optical pulse. The ablation energy should be chosen to be barely above the ablation threshold so that the formation of droplets or clusters can be minimized or avoided [12]. The target is placed at a distance $S_0 = 500$ mm from the optical standing wave region. The ablation laser beam is focused on the target to a small diameter of $d_0 = 5$–10 μm. An aperture of diameter $d_A = 1$ mm is placed in the atomic beam path (along z- or longitudinal direction) right before the standing wave region so that only normally incident portion of the atom plume is allowed to pass through. For the standing wave, we propose to use a cw laser with a beam diameter of 1 mm and a power up to 10 W. We focus the beam with a cylindrical lens along y-direction to a small waist $d_{sw} = 50$ μm behind the aperture. The beam is reflected with a cylindrical reflector. The incident beam and the reflected beam form the desired standing wave. After passing through the standing wave, the atomic beam is incident on a substrate at a focal distance behind the laser standing wave.

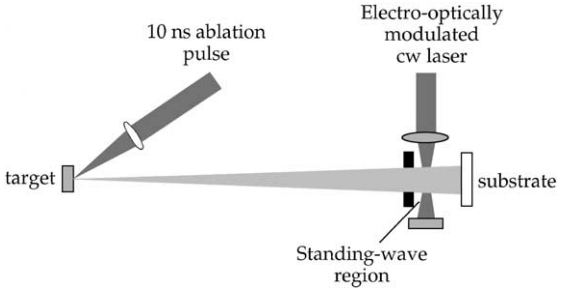

Fig. 1. Proposed experimental setup for fabricating 1-D and 2-D nano-structural arrays with a nanosecond ablation laser and a synchronously modulated cw laser standing wave.

We have recently shown [13,14] that atoms emitted from the center of the target form a periodic array of nano-wires on the substrate at a focal distance

$$S_1 = \frac{m\lambda^2 c}{64\pi^2 d_{sw}} \left(\frac{\varepsilon_0}{\alpha'}\right) \left(\frac{v_\ell^2}{I_0}\right). \quad (1)$$

Here m is the mass of the atom; λ is the wavelength of the laser standing wave; α' is the atomic polarizability of the atom at the optical wavelength; v_ℓ is the longitudinal velocity of the atom; I_0 is the intensity of the incidence laser beam (in unit of W/m^2). For a Ni atom with $\alpha'/\varepsilon_0 = 6 \times 10^{-28}$ m^3 and a mean longitudinal $\langle v_\ell \rangle = 7.4 \times 10^4$ cm/s, and using $\lambda = 1$ μm, we find that a cw laser of 2 W is required to focus the atoms at a focal length of $S_1 = 0.5$ mm. We numerically calculate the profile near the center of the substrate as shown in Fig. 2(a). The full-width-at-half-maximum (FWHM) is less than 4 nm. If we use two standing wave patterns that are orthogonal to each other, the calculated atom density profile changes to a nano-pillar with a nominal width of 4 nm as shown in Fig. 2(b).

We now show how an effective cooling along the longitudinal direction is achieved by modulating the temporal profile of the optical standing wave. With the target-substrate separation of $S_0 = 500$ mm, a pulsed atomic beam, produced at

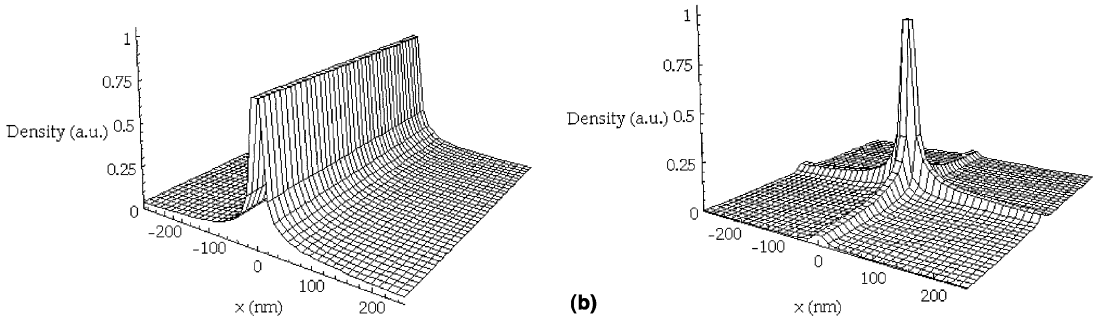

Fig. 2. (a) Calculated atom density profile on a substrate after a pulsed atomic beam is passed through a temporally modulated laser standing wave. The FWHM of the wire is 4 nm. The diffraction effect of the de Broglie wave of the atom broadens the FWHM to roughly 10 nm. (b) Calculated atom density profile on a substrate after a pulsed atomic beam is passed through two orthogonal laser standing waves. The FWHM of the column is 4 nm. Again the diffraction effect of the de Broglie wave of the atom broadens the FWHM to roughly 10 nm.

t_0 with laser-ablation, has a thermal longitudinal velocity distribution and arrives at the substrate over a time span of 500 μs. The arrival time of an atom in the beam with a longitudinal v_ℓ is $\Delta t = t - t_0 = S_0/v_\ell$. This means that fast atoms show up early while slow atoms show up late. Since the focal length $S_1 \sim v_\ell^2/I_0$ [see Eq. (1)], if we make the intensity of the incident laser beam I_0 to be time-dependent such that $I_0(t)/v_\ell^2 = I_0(t)(\Delta t/S_0)^2$ is kept constant, atoms with different longitudinal velocities will be focused with the same focal length. Let $\langle I_0\rangle$ be the intensity needed to focus an atom with $\langle v_\ell\rangle$, we find

$$I_0(t) = \langle I_0\rangle(S_0/\langle v_\ell\rangle)^2\Delta t^{-2} = \langle I_0\rangle(S_0/\langle v_\ell\rangle)^2(t-t_0)^{-2}. \quad (2)$$

In this way, we achieve effectively the longitudinal "cooling". In Fig. 3, we show the proposed temporal profile of an intensity-modulated cw laser standing wave. The modulation at this long time scale can be achieved precisely and easily with an electro-optic device. In this case, the vast majority of the atomic plume will be focused with the same focal length as given by Eq. (1), and we expect the profiles displayed in Figs. 2(a) and (b) to represent that of the entire pulsed atomic beam.

In our calculation, the atoms are treated classically. If we include the wave nature of the atoms, the de Broglie wavelength of the atoms and the proposed experimental geometry sets an additional limit (the diffraction limit) on how small the

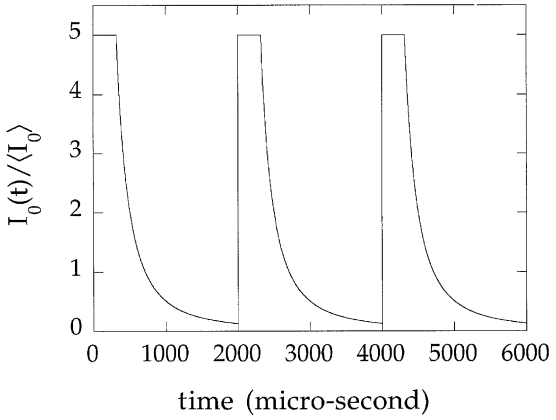

Fig. 3. Proposed temporal profile of the intensity of the laser standing wave. At $t_0 = 0$, 2000, 4000 μs, etc., the pulsed atomic beam is produced.

FWHM of a nano-wire can be made with this technique. For an Ni atom with $m = 9.7 \times 10^{-23}$ gm and a longitudinal $\langle v_\ell\rangle = 7.4 \times 10^4$ cm/s, the de Broglie wavelength is 0.009 nm. With the dimension of the "cylindrical atom lens" being 500 nm (one-half of the laser wavelength), at a focal length of $S_1 = 0.5$ mm = 500,000 nm away, the diffraction-limited Ni atom beam diameter is 9–10 nm. As a result, the actual FWHM of the wires in Fig. 2(a) or pillars in Fig. 2(b) are expected to broaden to 10 nm due to the diffraction effect of the de Broglie wave of the atoms.

To fabricate crystalline pillars as shown in Fig. 2(b), it is essential that the substrate supports the

crystalline structure. In addition, to maintain the aspect ratio of an as-deposited pillar against the diffusion over the step edges, it is preferable that a preferred crystalline face is perpendicular to the deposition direction. This will require the substrate to be crystalline and expose a particular surface plane. Furthermore the substrate temperature needs to be controlled to inhibit the diffusion across atomic step edges while allowing the diffusion along flat terraces to sustain crystalline growth.

Acknowledgements

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References

[1] G.L. Timp, R.E. Behringer, D.M. Tennant, J.E. Cunningham, Phys. Rev. Lett. 69 (1992) 1636.
[2] J.J. McClelland, R.E. Sholten, E.C. Palm, R.J. Celotta, Science 262 (1993) 877.
[3] R.W. McGowan, D.M. Giltner, S.A. Lee, Opt. Lett. 20 (1995) 2535.
[4] Th. Schultz, U. Drodofsky, B. Brezger, J. Stuhler, S. Nowak, T. Pfau, J. Mlynek, Atom optics, in: M.G. Prentiss, W.D. Phillips (Eds.), Proc. SPIE, vol. 2995, 1997, p. 80.
[5] K.K. Berggren, M. Prentiss, G. Timp, R.E. Behringer, J. Opt. Soc. Am. B 11 (1994) 1166.
[6] R. Gupta, J.J. McClelland, Z.J. Jabbour, R.J. Celotta, Appl. Phys. Lett. 67 (1995) 1378.
[7] J.H. Thywissen, K.S. Johnson, R. Younkin, N.H. Dekker, K.K. Berggren, A.P. Chu, M. Prentiss, J. Vac. Sci. Technol. B 15 (1997) 2093.
[8] R. Younkin, K.K. Berggren, K.S. Johnson, M. Prentiss, D.C. Ralph, G.M. Whitesides, Appl. Phys. Lett. 71 (1997) 1261.
[9] K.K. Berggren, A. Bard, J.L. Wilbur, J.D. Gillaspy, A.G. Helg, J.J. McClelland, S.L. Rolston, W.D. Phillips, M. Prentiss, G.M. Whitesides, Science 269 (1995) 1255.
[10] J.J. McClelland, R. Gupta, R.J. Celotta, G.A. Porkolab, Appl. Phys. B 66 (1998) 95.
[11] J.J. McClelland, R.J. Celotta, Thin Solid Film 367 (2000) 25.
[12] P. Ohresser, J. Shen, J. Barthel, M. Zheng, Ch.V. Mohan, M. Klaua, J. Kirschner, Phys. Rev. B 59 (1999) 3696.
[13] X.D. Zhu, Opt. Lett. 22 (1997) 1890.
[14] X.D. Zhu, Appl. Phys. Lett. 74 (1999) 525.