Writing a superlattice with light forces

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Abstract. In atom lithography the conventional roles played by light and matter are reversed. Instead of using a solid mask to pattern a light beam, a mask of light is used to pattern a beam of neutral atoms. In this paper we report the production of different chromium dot arrays with quadratic symmetry. The lattice period depends on the relative polarization and the phase of the two standing waves generating the light mask. A small angular misalignment of the laser beams breaks the high symmetry and a chromium superlattice is written, that is a continuous periodic change between two different quadratic lattices. The structures exhibit lines with a FWHM below 50 nm and clearly separated chromium dots with a FWHM below 70 nm.

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In 1992 atom lithography was first demonstrated at AT & T Bell Laboratories [1]. At the National Institute of Standards and Technology [2] and in our group [3], lines with the technologically interesting material chromium have been written with a period of $\lambda/2 = 213$ nm, where λ is the laser wavelength near an atomic resonance. The technique has been refined to write various two-dimensional structures of the same and larger periods [4, 5]. Shorter periods have been achieved in one [6] and two [7] dimensions by the use of polarization gradients in the light field or by a double exposure technique with detuning switch [8].

With the new setup presented in this paper we write clearly separated chromium dots in quadratic lattices. The periodicity and orientation of the lattice are determined by four laser beams forming the light mask, either as two independent standing light waves or as a four beam interference pattern. By slightly misaligning the orthogonal overlap of all four beams we are able to deposit the first superlattice structure produced by atom lithography.

1 Experimental setup

The basic elements used in atom lithography with light forces are shown in Fig. 1. A thermal beam of neutral chromium atoms is created by sublimating chromium in a high temperature effusion cell. In the next step the atomic beam is transverse cooled by Doppler- and polarization gradient cooling. The collimated beam has a divergence of less than 0.4 mrad [5] and propagates through the light mask which is located directly above the substrate. Here the induced dipole force is used to manipulate the trajectories of the neutral atoms. In Fig. 1 this light mask is generated by a single standing light wave acting as an array of cylindrical lenses for the chromium atoms, which are deposited as lines with a periodicity of $\lambda/2$ on the glass substrate. The structure widths on the substrate can be much narrower than the period of the mask. The produced chromium structures were analyzed with an atomic force microscope (AFM).
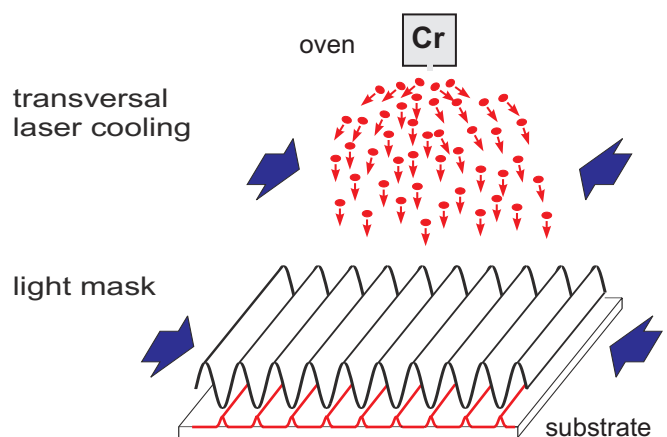

Fig. 1. Principle of atom lithography with light forces. The atomic beam is collimated by transverse laser cooling and then focused in a light mask onto the substrate
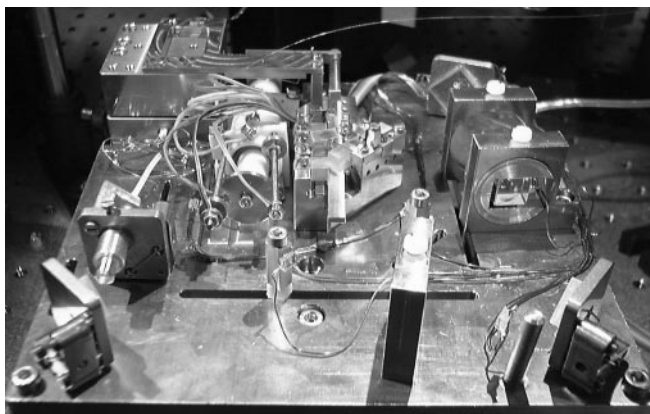
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Fig. 2. Photograph of the small optical table used to generate the light masks (45° mirror holder in the *center*) and manipulate the glass substrates (Burleigh Inchworm motor and a 3D piezo-actuator on the *upper left*). The light is coupled in via an optical single-mode fiber (output coupler *left*) which ensures a stable beam profile and position

Instead of using only a single standing light wave, a more complex setup mounted on a small optical table (see Fig. 2) inside the vacuum system was employed to generate the light mask. To perform more than one deposition per substrate a Burleigh Inchworm motor and a 3D piezo-actuator are used to translate the substrate with respect to the light mask. The light field configurations that have been used to generate the different quadratic lattices will be presented in the following sections together with the AFM measurements.

A detailed description of the experimental setup including the tunable laser system working on the chromium transition $^7S_3 \to \, ^7P_4$ at $\lambda = 425.6$ nm is given in [5]. To increase the laser intensity the two external resonators with $KNbO_3$ as a nonlinear material used in [5] were replaced by one cavity. In the new cavity, lithium tri-borate (LBO) is used as a nonlinear material to produce up to 600 mW at $\lambda = 425.6$ nm out of 2 W laser output power from the Ti:sapphire laser.

2 Quadratic lattice with $\lambda/2$ period

The light field configuration used for the production of a quadratic lattice with $\lambda/2$ period is formed by two standing light waves intersecting at an angle of 90° as shown in Fig. 3a. The polarizations of the two standing light waves are chosen to be orthogonal so that they add up in their intensities.

The experimental realization of the light mask by retro-reflecting one incoming laser beam in a compact setup of two mirrors mounted at an angle of 45° is shown in Fig. 3b. The calculated intensity pattern indicates two regions where the interfering laser beams form a single standing light wave with a period of $\lambda/2$. In front of mirror 1 a quadratic lattice with the same period is generated. The calculated intensity distribution is shown with a much exaggerated wavelength, to make the interference patterns visible.

In all experiments a Gaussian beam with a waist of 100 μm (half width at $1/e^2$ point) was used. In the direction along the atomic beam this Gaussian profile was cut by the
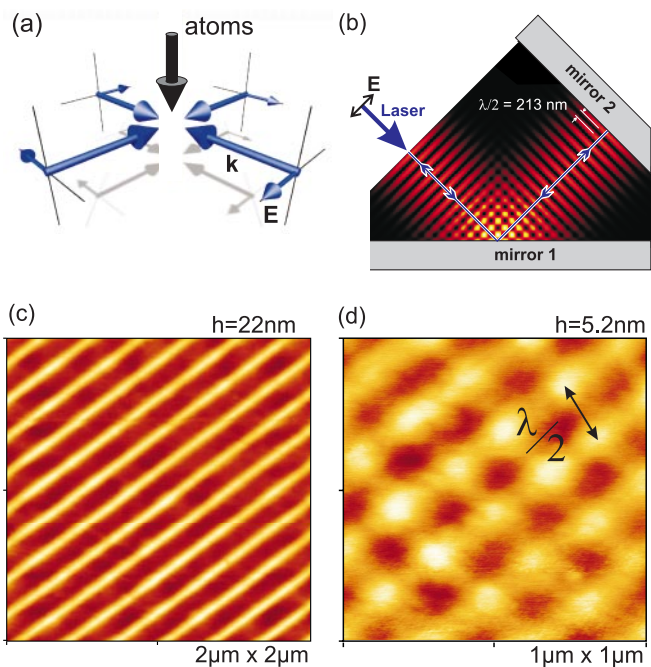

Fig. 3a–d. Quadratic lattice with $\lambda/2$ period: **a** light field configuration; **b** experimental realization; **c** AFM measurement of the $\lambda/2 = 213$ nm line structure; **d** AFM measurement of the quadratic dot structure with $\lambda/2 = 213$ nm period

substrate, so that 75% of the Gaussian beam power passed above the substrate. The deposition time for each sample was 10 min with a deposition rate of 2 nm/min at an oven temperature of 1650 °C.

Figure 3c shows an AFM measurement of the chromium lines with a period of $\lambda/2 = 213$ nm and a peak-to-valley height of 22 nm. The laser power of the incoming beam was 30 mW. To avoid spontaneous emission the detuning relative to the atomic transition was chosen to be $\Delta = -40\Gamma = -200$ MHz $\times 2\pi$. The average FWHM of the narrowest deposited lines is less than 50 nm. An AFM analysis of the structure generated on the substrate by overlapping two standing light waves is presented in Fig. 3d. Here we measure a quadratic lattice which matches the calculated intensity pattern shown in Fig. 3b.

3 Quadratic lattice with $\lambda/\sqrt{2}$ period

To increase the structure period we changed the polarizations of the four laser beams to be perpendicular to the substrate plane as shown in Fig. 4a. This is realized by rotating the polarization of the incoming laser beam (Fig. 4b). The calculated intensity pattern in Fig. 4b indicates that due to interference effects the orientation and period of the resulting lattice are changed with respect to the pattern in Fig. 3b.

Figure 4c shows an AFM measurement of the substrate region in front of mirror 1. Clearly separated chromium dots (FWHM = 100 nm) are found on a quadratic lattice with a period of $\lambda/\sqrt{2} = 300$ nm. The power of the Gaussian laser beam was 21 mW and the detuning $\Delta = -200$ MHz $\times 2\pi$.
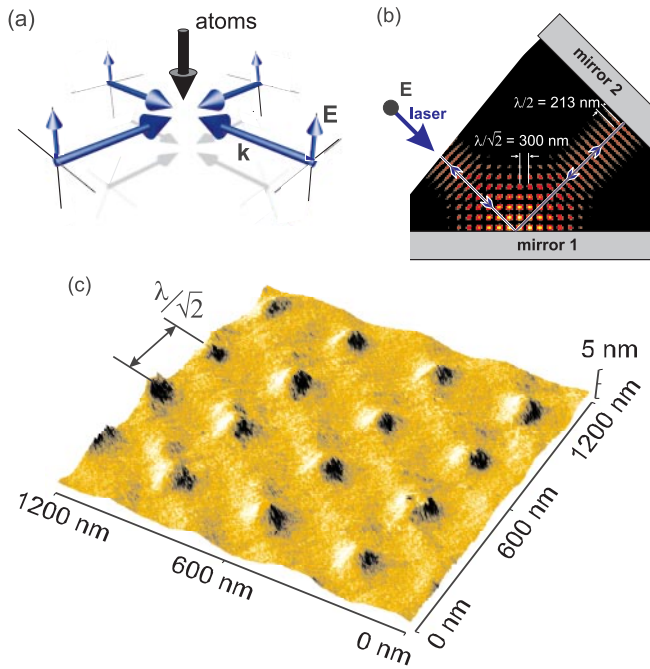
Fig. 4a–c. Quadratic lattice with $\lambda/\sqrt{2}$ period: **a** light field configuration; **b** experimental realization; **c** AFM measurement of the lattice with $\lambda/\sqrt{2} = 300\,\text{nm}$ period. The chromium dots have a FWHM of $100\,\text{nm}$

4 Superlattice

In the previuos two sections it was shown how the relative polarizations of the four laser beams change the orientation and periodicity of the chromium lattice. The $\lambda/2$ lattice was deposited with a light mask consisting of two independent standing light waves. For the $\lambda/\sqrt{2}$ lattice, an interference pattern with four laser beams that were polarized perpendicular to the substrate plane was used.

Another way of switching between these two lattice periods is to change the relative phase between the two standing light waves. In the situation of Fig. 4b the boundary conditions at the mirrors together with the high symmetry result in a relative phase of zero. This leads to the shown period of $\lambda/\sqrt{2}$. When the phase is $\pi/2$ the two standing light waves add up in their intensities and an interference pattern with a period of $\lambda/2$ is formed.

In the experiment we realized spatial phase changes by breaking the high symmetry of the light field configuration used in the former sections. This is achieved by slightly misaligning the angle of incidence of the incoming laser beam on mirror 1 with respect to Fig. 4b by an angle α (Fig. 5a). The resulting wave vectors are shown in Fig. 5b. All four light beams are polarized perpendicular to the substrate plane. Figure 5d shows how the four light vectors k_1, k_2, k_3, and k_4 can be separated in two perpendicular standing light waves $\cos k'_1 \cdot r$ and $\cos k'_2 \cdot r$ and a relative phase factor $\mathrm{e}^{\mathrm{i}(k''_1 - k''_2) \cdot r}$ between them. In the experiment the angle α is chosen to be small so $|k'_1| = |k'_2| \approx |k_1| = |k_2|$ and the two-dimensional light mask has nearly the same period as in previous sections. As $|k''_1| = |k''_2| \ll |k'_1| = |k'_2|$ the lattice period of the superlattice $\Lambda = \lambda/(\sqrt{2}\sin\alpha)$ is three orders of magnitude larger then the period in the light mask.
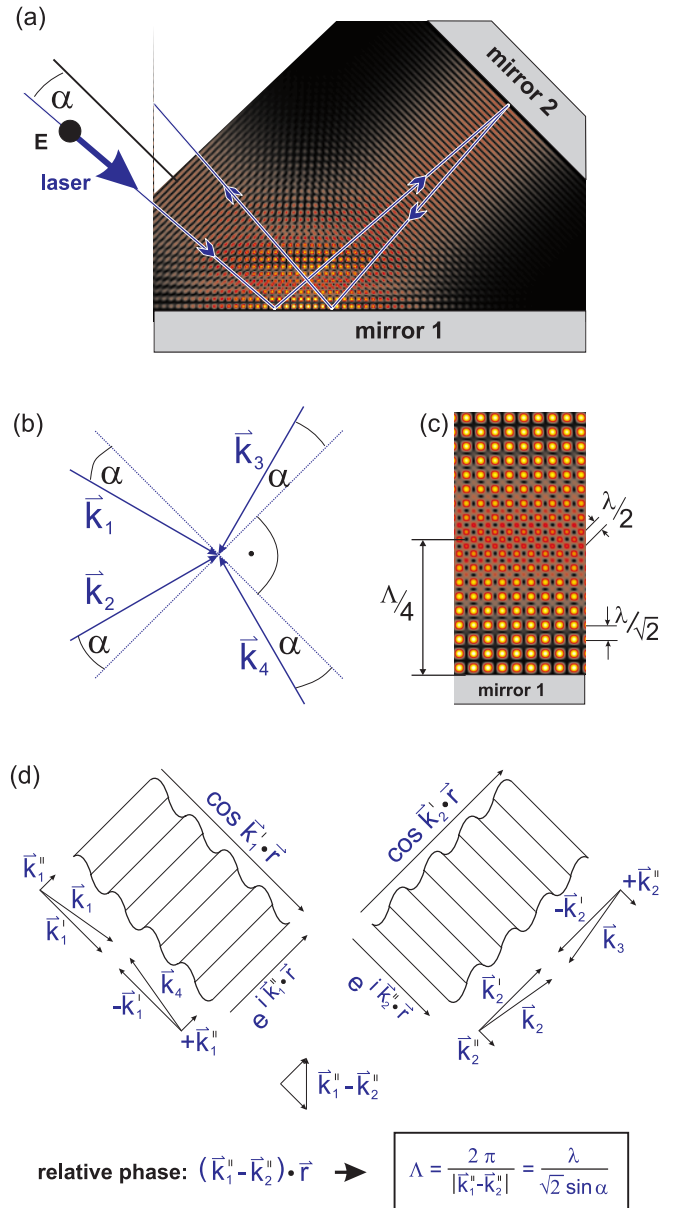

Fig. 5a–d. Superlattice: **a** light field configuration with broken symmetry due to a misalignment of the incoming laser beam by an angle α. **b** wave vectors **c** calculated intensity distribution of the light field in front of mirror 1. **d** explanation of the superlattice period Λ, as described in the text

$$\text{relative phase: } (\vec{k}''_1 - \vec{k}''_2) \cdot \vec{r} \quad \longrightarrow \quad \Lambda = \frac{2\pi}{|\vec{k}''_1 - \vec{k}''_2|} = \frac{\lambda}{\sqrt{2}\sin\alpha}$$

A calculation of the resulting intensity pattern is shown in Fig. 5a and c. In front of mirror 1 the relative phase is zero and the lattice period is $\lambda/\sqrt{2}$. At a distance $\Lambda/4$ from the mirror the relative phase is shifted from 0 to $\pi/2$ and, therefore, a $\lambda/2$ lattice is formed. Then the phase increases to π which revives the interference of all four laser beams and a lattice period of $\lambda/\sqrt{2}$ in the intensity pattern. Compared to the zero phase intensity distribution, the maxima and minima change places.

The AFM analysis of a chromium structure formed by this superlattice is shown in Fig. 6. For this deposition the power of the incoming laser beam was $34\,\text{mW}$ and the detuning $\Delta = +200\,\text{MHz} \times 2\pi$. A series of AFM pictures were captured on a line perpendicular to mirror 1. The distance be-
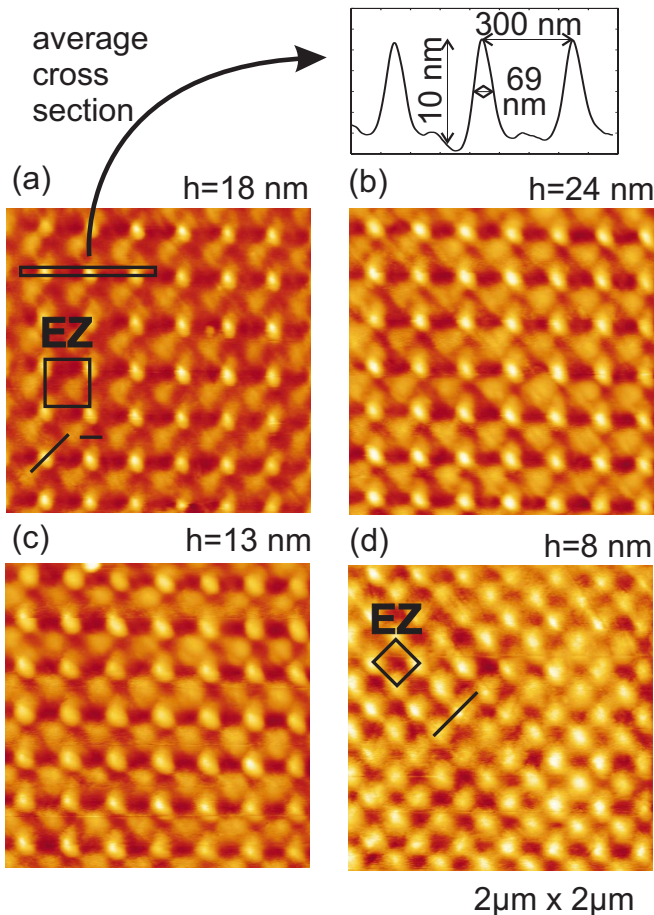
average cross section

300 nm

10 nm

69 nm

(a)   h=18 nm

EZ

(b)   h=24 nm

(c)   h=13 nm

(d)   h=8 nm

EZ

2µm x 2µm

Fig. 6a–d. Superlattice: The AFM pictures were captured on a line perpendicular to mirror 1 with an equidistant frame spacing of $\sim 16\,\mu m$. Starting with the zero phase pattern in **a** with a lattice period of $\lambda/\sqrt{2} = 300\,nm$ a continuous transition from **b** through **c** to the $\pi/2$ phase with the $\lambda/2 = 213\,nm$ periodicity in **d** can be seen

tween the images was chosen to be $\sim 16\,\mu m$. The AFM picture in Fig. 6a shows the position in front of mirror 1 with the zero phase pattern and the lattice period of $\lambda/\sqrt{2} = 300\,nm$. The AFM pictures Fig. 6b and c show the continuous transition to the $\pi/2$ phase pattern with the $\lambda/2 = 213\,nm$ periodicity in Fig. 6d. The average cross section of three dots in Fig. 6a shows that the chromium dots exhibit a FWHM of less than 70 nm. The superlattice period was measured

to be $200\,\mu m$ which corresponds to a misalignment angle of $\alpha \sim 1.5\,mrad$.

5 Conclusion

In this paper we have presented the first superlattice structure produced by atom lithography. With a superlattice period of $200\,\mu m$ the quadratic chromium lattice changes orientation and periodicity from $\lambda/\sqrt{2} = 300\,nm$ to $\lambda/2 = 213\,nm$. The FWHM of the narrowest chromium dots is less then 70 nm and, therefore, they are clearly separated. The combination of narrow dots and large lattice periods should make it possible to write a pattern in each unit cell by a translation of the substrate with respect to the light mask.

In a current experiment we want to make use of the fact that light masks are material selective. This special feature of light masks will allow depositions of a homogeneous and a structured layer at the same time, resulting in an artificial material with a structured doping on a sub-100 nm length-scale. Such a material is a promising candidate for a photonic crystal [9] or a quantum computer [10].

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