

## Atom “Pinhole Camera” with Nanometer Resolution

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Received September 21, 2006

An atom “pinhole camera” with nanometer resolution has been experimentally implemented for the first time. Owing to the use of this camera, an array of  $\sim 10^6$  identical nanostructures of Cr atoms with a characteristic size of the nanostructure less than 50 nm has been created on a glass surface. Nanostructures of arbitrary shapes have been created.

PACS numbers: 03.75.Be, 81.16.-c

DOI: 10.1134/S0021364006200124

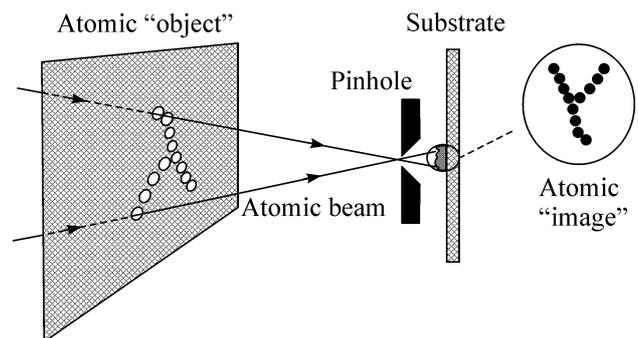
The most efficient method for controlling the motion of material particles in experimental physics is the use of interaction potentials with electromagnetic fields. The static magnetic and electric interaction potentials are used in the optics of charged particles [1]. In the recently appearing optics of neutral atomic beams [2, 3], various interaction potentials of atoms with laser and electromagnetic fields are used in addition to the static fields. The effective methods of diffraction, interference, mirror reflection of atoms, as well as the deep cooling and localization of atoms using dissipative methods of action on the motion of atoms, are implemented in atom optics [4]. The most difficult problem in atom optics is the problem of high-resolution focusing of neutral atoms, which is promising for the nondestructive method for controlling and probing the surface at the atomic molecular level, as well as for the creation of atomic and molecular nanostructures on the surface.

Although there are many proposals for focusing of atomic beams [5–9], this problem is experimentally unsolved. The main difficulty is the creation of the interaction potential of the atom with the electromagnetic field that is close to an “ideal” lens for atoms in its properties.

In this work, we experimentally implement another approach to the problem of focusing and construction of an image in atom optics, which is based on a well-known idea of “pinhole camera” in light optics and is also used in current experimental physics in rare cases when the creation of the focusing potential is difficult [10]. Nanometer resolution has been achieved for the first time. Owing to the use of the atom pinhole camera implemented in this work, an array of identical nanostructures with a characteristic size of a separate nanostructure less than 50 nm is created on the solid surface.

The pinhole camera in optics is a camera without lens. Light forming an image passes through a pin hole. In order to obtain sufficiently clear images, the aperture of such camera must be a small hole. Owing to the small aperture of pinhole cameras, exposition times long as compared to traditional cameras are required.

Figure 1 shows the layout of the experiment with the atom pinhole camera. The Cr atomic beam passes through a set of holes in a metal mask and thereby forms, by analogy with optics, a glowing object of a given geometry. The atoms pass through the holes in the mask, propagate in vacuum along rectilinear trajectories, similar to light rays, and are incident on a thin film (thickness  $h = 5 \mu\text{m}$ ) placed at a distance of  $L = 90 \text{ mm}$  from the mask with a large number ( $n \sim 3 \times 10^7 \text{ cm}^{-2}$ ) of conical holes (with the entrance diameter



**Fig. 1.** Layout of the atom pinhole camera. The Cr atomic beam passes through a set of holes in the metallic mask, thus forming a glowing object of a given geometry. The atoms pass through holes in the mask, propagate along rectilinear trajectories in vacuum, and are incident on the thin film with holes. Each hole of the film is a pinhole camera for atoms, which forms the inverted image of the object on the substrate surface.

$d \cong 50$  nm and exit diameter  $D \sim 350$  nm). Each hole of the film is a pinhole camera for atoms, which forms its individual image of the object on the substrate surface placed at a distance of  $l = 5$   $\mu\text{m}$  behind the film. In this geometry, a set of the images of the object, which are decreased by a factor of about  $m = L/l = 8000$  and are formed by Cr atoms sputtered on the surface, is created on the substrate.

An electrothermal atomic gun with the direct heating of an evaporator was used as a source of the thermal Cr atomic beam. The residual pressure in the vacuum chamber was equal to about  $4 \times 10^{-6}$  Torr. The evaporator was manufactured from molybdenum and had an inner diameter of 3.5 mm. The Cr atom flux in the film plane was approximately equal to  $10^{13}$  atoms/cm s at a working gun temperature of about 1350°C.

The metallic mask forming the object was placed in the immediate vicinity of the source of atoms. The mask was produced from a tantalum foil 50  $\mu\text{m}$  in thickness with a set of holes specifying the shape of the object. Masks with two hole configurations were used in the experiment: (i) those forming a cross of holes 0.5 mm in diameter and (ii) a  $\lambda$  mask with holes 250  $\mu\text{m}$  in diameter that form the  $\lambda$  letter (which is the symbol of the Institute of Spectroscopy).

As the thin film with holes, we used a track membrane of an asymmetric structure [11, 12]. The initial material for the track membrane was a Hostaphan RE5 (Hoechst AG) polyethylene terephthalate film 5- $\mu\text{m}$  thick. The film was irradiated by a 253-MeV accelerated krypton ion beam at the U-400 accelerator, Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research. Then, the film was irradiated by ultraviolet radiation from one side; after that, chemical etching in a 3M NaOH solution with the addition of 0.05% of Dowfax 2A1 surface active substance was performed at a temperature of 70°C. The use of the surface active substance ensured the creation of pores with a sharp narrowing near the surface that was not irradiated by ultraviolet radiation [11, 12].

Glass substrates with a surface roughness of no worse than 1 nm were used for sputtering. The structures created in the experiment were analyzed by means of an atomic force microscope developed at the Institute of Spectroscopy [13]. The atomic force microscope ensured a resolution of 10 nm along the surface and a resolution of 0.1 nm of the height of an object.

The conical shape of the holes of the track membrane was chosen in order to increase the angle of view  $\alpha = 2 \arctan \frac{d+D}{2h}$  ( $\sim 4.5^\circ$ ). On the one hand, this leads to an increase in the number of images of the object, which is determined by the number of pinhole cameras passing the atomic beam,  $N \approx \alpha^2 L^2 n$  ( $\sim 10^6$ ). On the other hand, for large angles of view, it is possible to create the images of complex geometry, which is characterized by the maximally allowable number of holes in the mask,

$N_R = (l\alpha)^2/d^2$ . This number can generally be made large owing to an increase in the distance between the pinhole camera and substrate. However, this leads to a decrease in the profile height of created nanostructures at a given exposition, as well as to an increase in the atomic diffraction effect. The increase in the angle of view  $\alpha$  makes it possible to reduce requirements to the strict parallelism of the axes of the holes in the track membrane that are determined by the production technology, as well as to the adjustment accuracy in the experiment.

In the described geometry of the experiment, each pinhole camera creates an image point on the surface plane with a shadow of the radius

$$a = \frac{dL+l}{2L} = \frac{d}{2} \left( 1 + \frac{1}{m} \right).$$

The geometrical atom optics approximation is applicable when the following condition is valid on diffraction restriction for atoms with the de Broglie wavelength  $\lambda_{\text{dB}}$ :

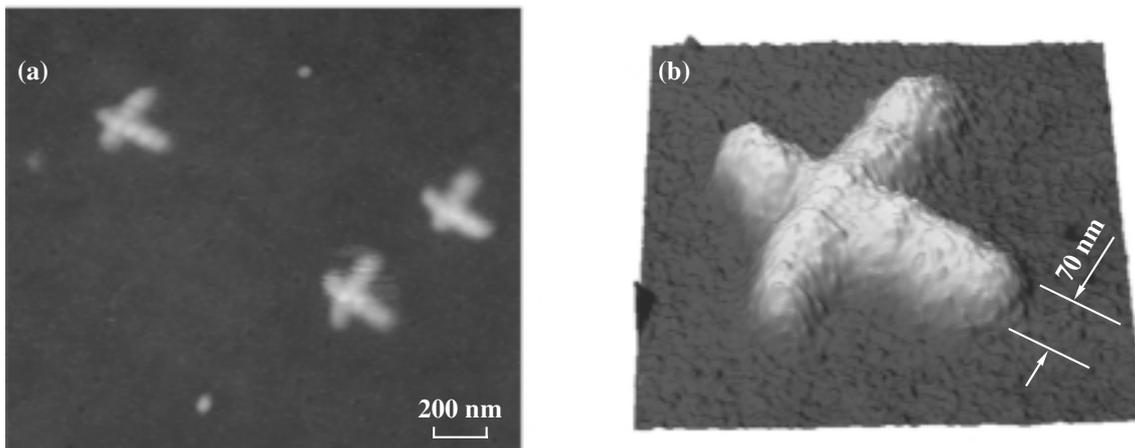
$$1.22 \frac{\lambda_{\text{dB}}}{d} l \ll d \left( 1 + \frac{1}{m} \right), \quad (1)$$

In this case, an image is an inverted copy of the object decreased by  $m$  times and has a resolution of about  $d \sim 50$  nm, which allows the creation of nanometer structures in the experiment. The mean atomic velocity in the beam in the experiment was equal to about 900 m/s, which corresponds to the de Broglie wavelength  $\lambda_{\text{dB}} = 0.08$  Å. Thus, condition (1) is satisfied, and the atomic diffraction in the experiment can be disregarded.

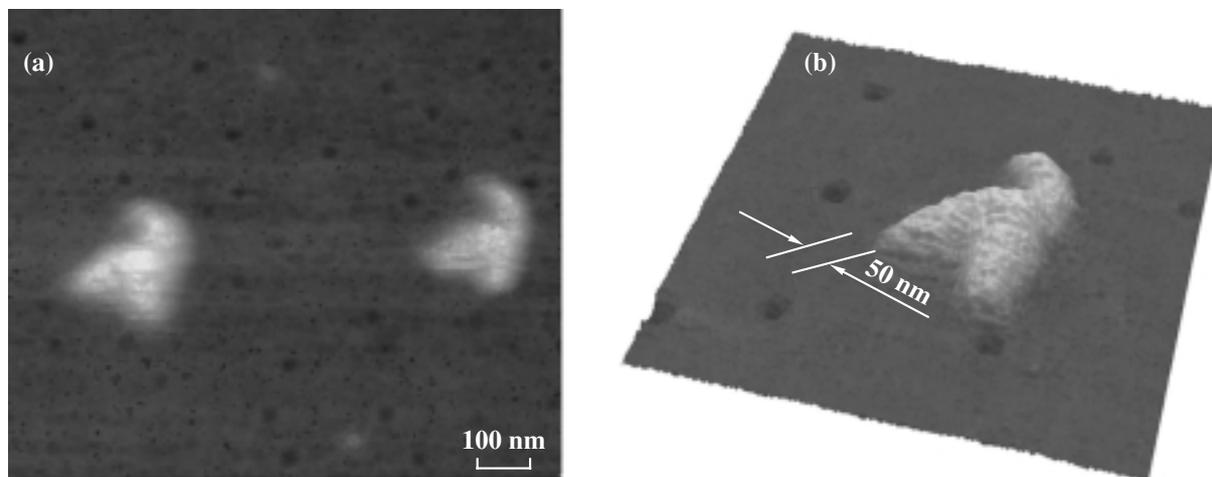
Figures 2 and 3 shows the images of the nanoobjects created in the experiment by the method described above. As seen in the figures, structures similar in shape to the corresponding object mask are formed in the experiment. The profile height for each structure is equal to about 10–20 nm for an exposition time of 15 min.

Figure 2a shows the  $2 \times 2$   $\mu\text{m}$  surface section filled with the images of the "cross" object. In addition to the almost completely formed cross images, the figure also exhibits structures with images of only its part. This occurs owing to the partial blocking of atoms forming the image of the cross of atoms and because the axes of various holes of the track membrane are nonparallel to each other. The geometry of the most complete crosses corresponds to an angle of view of about  $2^\circ$  of the pinhole camera. This value is slightly smaller than the expected value and is likely explained by the difference of the profile of the track membrane from the ideal cone.

Figure 2b shows the detailed image of a simple cross. As seen in the figure, the cross consists of partially destructed nanostructures that are images of separate holes of the object mask. According to the distance between the vertices of neighboring nanostruc-



**Fig. 2.** Nanostructures of Cr atoms on the glass surface that are obtained using the pinhole camera and cross object. Sections of the sizes (a)  $2 \times 2 \mu\text{m}$  and (b)  $800 \times 800 \text{ nm}$  are shown. The nanostructures are measured by means of the atomic force microscope.



**Fig. 3.** Nanostructures of Cr atoms on the glass surface that are obtained using the pinhole camera and lambda object. Sections of the sizes (a)  $1 \times 1 \mu\text{m}$  and (b)  $500 \times 500 \text{ nm}$  are shown. The nanostructures are measured by means of the atomic force microscope.

tures, the image is decreased by a factor of about 8000, which confirms the above estimates, as well as the validity of the applicability of geometrical atom optics given by Eq. (1). The ground width of the nanostructures is approximately equal to 110 nm, which well corresponds to the passage of the atomic beam through the holes of pinhole cameras and is determined by the sum of its entrance diameter  $d = 50 \text{ nm}$  and the mask image diameter  $d_0 = 0.5 \text{ mm}/8000 = 62 \text{ nm}$ . The full width at half maximum is equal to 70 nm.

Figure 3 shows the experimental results obtained with the lambda mask. This mask is smaller than the cross mask and corresponds in sizes to the experimentally measured angle of view for used pinhole cameras, which leads to an increase in the fraction of complete unvignetted images. As seen in the figure, the full width

at half maximum and ground width of the formed nanostructures in the base are equal to 50 and 70–80 nm, respectively, which are smaller than those in the preceding case and are explained by smaller diameters of the holes in the mask used in this case.

In summary, a new approach has been proposed to construct images in atom optics that is based on a pinhole camera well-known in traditional light optics. The method resolution is equal to 50 nm. The construction of the images of one object has been experimentally implemented with Cr atoms using a large number,  $\sim 10^6$ , of pinhole cameras. This approach makes it possible to create  $10^6$  identical structures or Cr atoms with a characteristic structural-element size of about 50 nm. The advantages of the proposed method are (i) the simplicity of experimental implementation, (ii) high spatial

resolution in the absence of geometric and chromatic aberrations, (iii) the possibility of using thermal atomic and molecular beams, and (iv) universality (the absence of the fundamental constraints on the choice of the sort of particles), as well as the sufficiently high efficiency and possibility of creating a large number of identical nanostructures. The problems of the limiting resolution of the atom pinhole camera will be discussed elsewhere.

This work was supported in part by the Russian Foundation for Basic Research (project nos. 05-02-16370-a, 06-02-16301-a, and 06-08-01299-a) and by the U.S. Civilian Research and Development Foundation (grant no. RU-P1P-2572-TR-04).

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*Translated by R. Tyapaev*

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