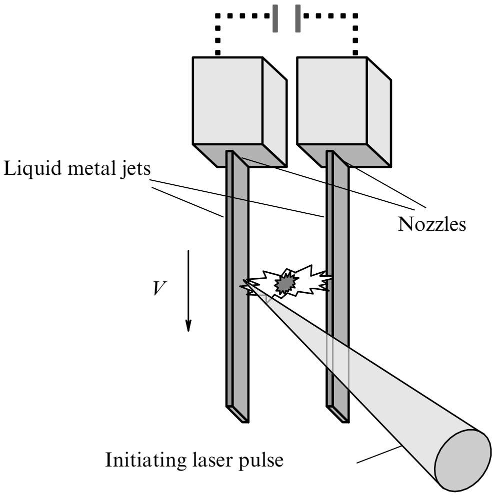

Figure 6. Schematic representation of the 'jet' EUV radiation source.

dozen meters per second, thereby ensuring nozzle cooling and the heat removal.

The voltage is applied across the jets, and the discharge between them occurs when laser radiation is focused onto one of them (Fig. 6). Not only do the jets remove the heat released in the discharge, but they also efficiently cool the metal elements closest to the discharge — the nozzles. The jets end up in the heat exchanger and return to the system after cooling with the aid of pumps. The power resource of this technical solution amounts to 200 kW.

In the foregoing, we discussed several approaches to the solutions of two problems — increasing the radiation power (the thermal load), and improving the radiation dose stability. Lying outside of the scope of our report were such important aspects of lithographic apparatus development as the lifetimes of the electrodes and optical elements, primarily, the radiation collector. The latter problem is directly related to the physics of the radiation source, because it arises from the so-called debris — corpuscular streams (atoms, ions, droplets of electrode material) emanating from the discharge region.

The demonstration EUV lithography apparatus (the so-called alpha tool) has already been made and is familiar to the industry. However, its main parameters are lower by a factor of ten or more than the parameters complying with the HVM requirements. The industry has allowed researchers the relatively little leeway of two years to overcome this gap.

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DOI: 10.1070/PU2007v050n07ABEH006322

Parallel fabrication of nanostructures via atom projection

V I Balykin

1. Introduction

There are two radically different approaches to the development of nanotechnology. These approaches are commonly referred to as the 'top down' and 'bottom up' technologies. The top down approach involves reducing the dimensions of physical bodies to objects with nanometric parameters. For instance, semiconductor microelectronic devices are fabricated by the optical lithography technique whereby the intermediate product is processed by a laser beam and the minimal dimension of the elements of the created microelectronic circuit is defined by the laser radiation wavelength. We note that the diffraction limit of the resolution of conventional optical lithography is about 65 nm. There are several other approaches to top down technology, each of them possessing both advantages and disadvantages: charged-particle beam lithography encounters problems associated with batch production of structures and the significant part played by Coulomb repulsion; self-organizing fabrication still calls for a better understanding of the physical processes.

Bottom up technology consists in the nanoobject under fabrication being 'assembled' of individual atoms, molecules, biological cells, etc. The feasibility and promise of this approach was first pointed out by Richard Feynman in his report to the annual meeting of the American Physical Society in 1959 [1]. The practical realization of bottom up technology became possible with the development of the probe microscopy technique which enabled not only observations of nanoobjects with atomic resolution but also manipulations of single atoms and molecules. This was first accomplished by researchers at an IBM laboratory, who managed to inlay their company's name (IBM) with 35 xenon atoms on the surface of a nickel single crystal [2]. This technique opens up many possibilities for manipulations at the level of individual atoms and molecules. However, methods reliant on the employment of scanning probes are generally characterized by low productivity and high cost.

Fabricating nanostructures with a size of about 10 nm presents a complex technological problem which is important from both the practical and theoretical viewpoints, because these structures bridge the gap between the classical and quantum-mechanical worlds.

2. Atom optics and atom nanooptics

Atom optics is an alternative approach to nanotechnology based on the bottom up principle. Atom optics is the optics of material particles (along with electron, ion, and neutron optics) and it concerns with the problems of formation of the ensembles and beams of neutral atoms, control over them, and their application. The term *atom optics* is similar to the terms *light optics* or photon optics. Basically, atom optics relies on three main techniques: the first depends on atom – matter interactions, the second on the interaction between atoms having a magnetic or electric dipole moment and a static electric or magnetic field, and the third on the resonance (or quasiresonance) interaction between an atom and an optical field.

As a result of intensive development during the last 10–15 years, atom optics has become an important part of atomic, molecular, and optical physics, making contributions to different technologies [3–10]. Among important areas of atom optics is the development of basic elements similar to the well-known elements of ordinary light optics, like atom lenses, mirrors, beam splitters, and interferometers, as well as the application of these elements in practical devices. In particular, one of the numerous applications of atom-optics elements — *atom lithography* — is of considerable interest for the micro- and nanofabrication of material structures. In atom lithography, the internal and (or) external degrees of freedom of individual atoms are controlled by external electromagnetic fields with nanometer precision, making it possible to produce structures on the surface. This method offers several advantages over other methods, because it makes use of neutral atoms. First and foremost the fundamental spatial resolution limit inherent in this method is imposed by diffraction and proves to be extremely short, because atoms have relatively large masses and accordingly short de Broglie wavelengths. Furthermore, Coulomb repulsion forces are absent when use is made of neutral atoms. Lastly, it is possible to realize manipulation of atoms in parallel, making it possible to simultaneously treat relatively large surfaces. The possibility of depositing atoms on a surface with atomic precision by atom-optics techniques was first pointed out by Balykin and Letokhov [11, 12].

We will consider below the main nanostructure fabrication techniques utilized in atom optics.

2.1 Atom fabrication of nanostructures based on traveling and standing light waves

In recent years, several proposals have been made and a series of experiments have been conducted on the nanofabrication of atomic structures by atomic beams focused with the help of traveling and standing light waves [11–26]. By and large, it is possible to indicate two main ideas of focusing atoms by the laser radiation of traveling and standing light waves. One of them is the focusing of atoms by *a single laser beam*, which was first realized with the use of a sodium atomic beam [13, 14] and a Gaussian laser beam which played the part of an atom lens. This technique was extended to other atoms and differently configured laser beams, including so-called hollow beams [11, 12, 15, 16]. Figure 1a schematically depicts the focusing of atoms on a domain measuring several angströms using the TEM_{01}^* laser mode. In the propagation of atoms inside a hollow laser beam there occurs their focusing under the gradient force of light pressure. The atomic density distribution (Fig. 1b) over the focal plane of this atom lens has a width on the order of one angström, i.e., it is comparable to atomic dimensions [11, 12].

Another idea of constructing nanostructures involves the focusing of atoms by a standing laser radiation wave [17–26], which is of particular interest for the fabrication of periodic submicrometer structures. The first demonstration of atomic structure deposition by a standing light wave was given with sodium atoms [17]. McClelland et al. [21] deposited submicrometer-wide strips of chromium atoms. Figure 2a schematically shows the focusing of atoms by a standing light wave, and Fig. 2b displays the deposited strips of chromium atoms, which are significantly narrower than the radiation wavelength.

2.2 Fabrication of atomic nanostructures on the basis of laser nanofields

Atom optics reliant on traveling and standing laser fields has several fundamental and technical restrictions arising from the spatially nonlocalized nature of the laser light fields. The nonlocalizability of the laser light field is responsible for the nonlocalizability of atom-optics elements. This gives rise to imperfections in atom-optics elements: aberrations of atom lenses, low diffraction efficiency of atomic waves, limitations on the contrast ratio for interference fringes in atomic interferometers, etc.

It is clear from general physical considerations that the use of spatially localized atom–field interaction potentials is preferable in the construction of atom-optics elements, the atom lens in particular. Only three types of laser fields with sufficient spatial localization are known today: (i) a surface light wave which emerges in the total internal reflection of light (one-dimensional localization of light); (ii) the light field which emerges in the diffraction of light by structures shorter than the light wavelength (two-dimensional localization of light); (iii) the light field localized in partially open waveguides — a 'photon dot' and a 'photon hole' (three-

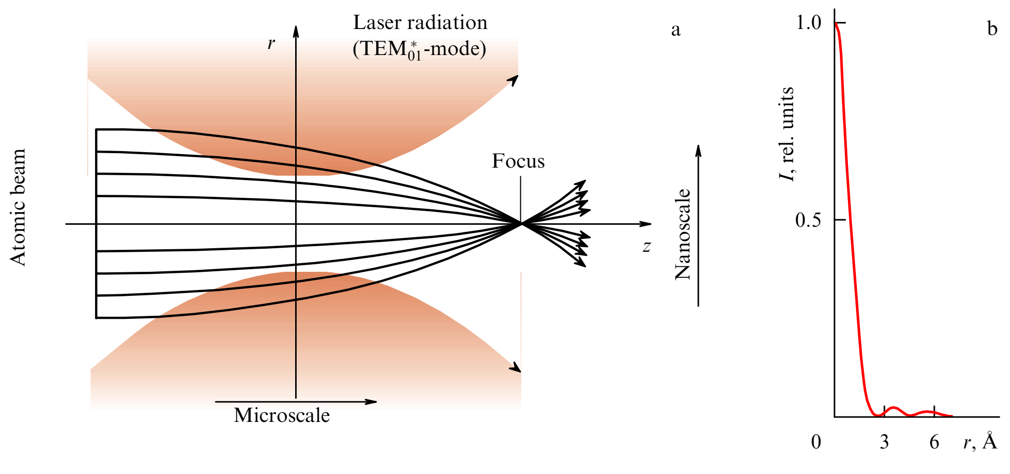

Figure 1. (a) Focusing of atoms on an angström-sized domain using the TEM_{01}^* mode. (b) Atomic density distribution with a width of about 1 Å in the focal plane of the atom lens.

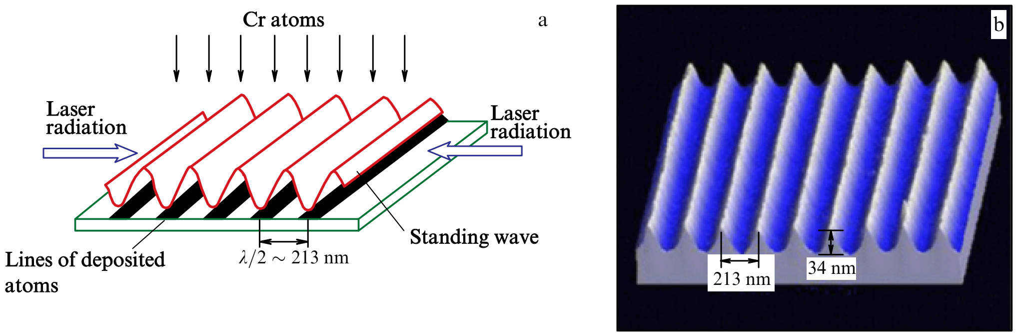

Figure 2. (a) Schematic sketch of the focusing of atoms by a standing light wave. (b) Deposited strips of chromium atoms with submicrometer widths.

dimensional localization of light). The last two laser nanofields have found application in atom lithography.

2.2.1 Atom lens on the basis of a Bethe hole. The best-known example of two-dimensional light localization is given by the Bethe aperture: a hole in a thin conducting screen with a diameter much smaller than the radiation wavelength [27–30]. The feasibility of applying such a nanolocalized field for the purposes of focusing atomic beams was studied in Refs [31–34]. It was shown [32–35] that a set of near-field microlenses may be employed to fabricate micro- and nanostructures on a surface.

A single near-field atom lens is schematically shown in Fig. 3a. Laser light is incident on a conducting screen with a hole smaller in diameter than the light wavelength. The field at the upper side of the screen consists of a traveling wave and the near-field component. The latter exhibits the follows remarkable features: (1) the magnitude of the near-field component in the immediate vicinity of the hole is on the order of magnitudes of the incident field; (2) the near-field component decays outside of the screen for a characteristic length on the order of the hole size, and (3) the near-field component possesses axial symmetry in a plane parallel to the screen and its magnitude varies approximately as the distance squared from the axis to the hole. The exact formal solution to the problem of plane wave diffraction by a round aperture in an infinitely thin metal plane was obtained in Refs [27–30]. Figure 3b demonstrates the near-field distribution of the light field.

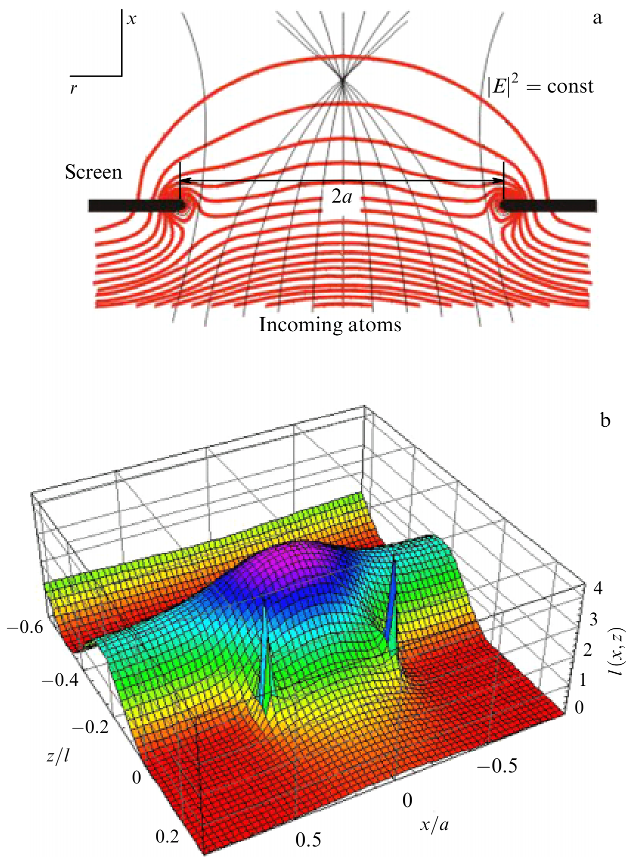

Figure 3. (a) Atom lens on the basis of light diffraction by the Bethe hole. (b) Near-field intensity distribution of the light field in the diffraction of light by the Bethe hole.

An analysis of near-field atom focusing [32–35] has revealed that efficient focusing may be accomplished for a relatively slow atomic beam. For a high atomic velocity, the short time of atom–field interaction confines the effect of the field on the atom, while for a low atomic velocity, the at-the-focus atomic beam dimension is limited by diffraction. The minimal focal spot size is defined by several factors which include: (1) spherical aberrations; (2) chromatic aberrations; (3) diffraction of atoms by the aperture; (4) the finite divergence of the incident atomic beam; (5) the interatomic interaction for a sufficiently high density, and (6) spontaneous emission. When these factors are taken into consideration, the focal spot size is equal to 0.1 of the optical wavelength.

2.2.2 Atom lens based on the 'photon dot' and 'photon hole'. A significant drawback of a field localized near an individual hole employed as an atom microlens is the fact that this field is inseparably linked with the field of the attached standing wave. In the motion of atoms in this domain, spontaneous decay processes may occur, which are ordinarily undesirable in atom lithography problems. We have investigated new types of spatially localized laser light fields with a characteristic dimension lying in the nanometer range, which are free from the above drawback [34, 36].

The scheme for obtaining this spatially localized light nanofield is depicted in Fig. 4a. Two plane conducting screens spaced at a distance of the order of or shorter than the light wavelength make up a planar two-dimensional waveguide for the laser radiation injected into it from one side. As is well known, for a waveguide consisting of two perfectly conducting parallel planes there exist solutions of the Maxwell equations which permit radiation propagation through a waveguide of arbitrarily small thickness d, including that significantly smaller than the radiation wavelength.

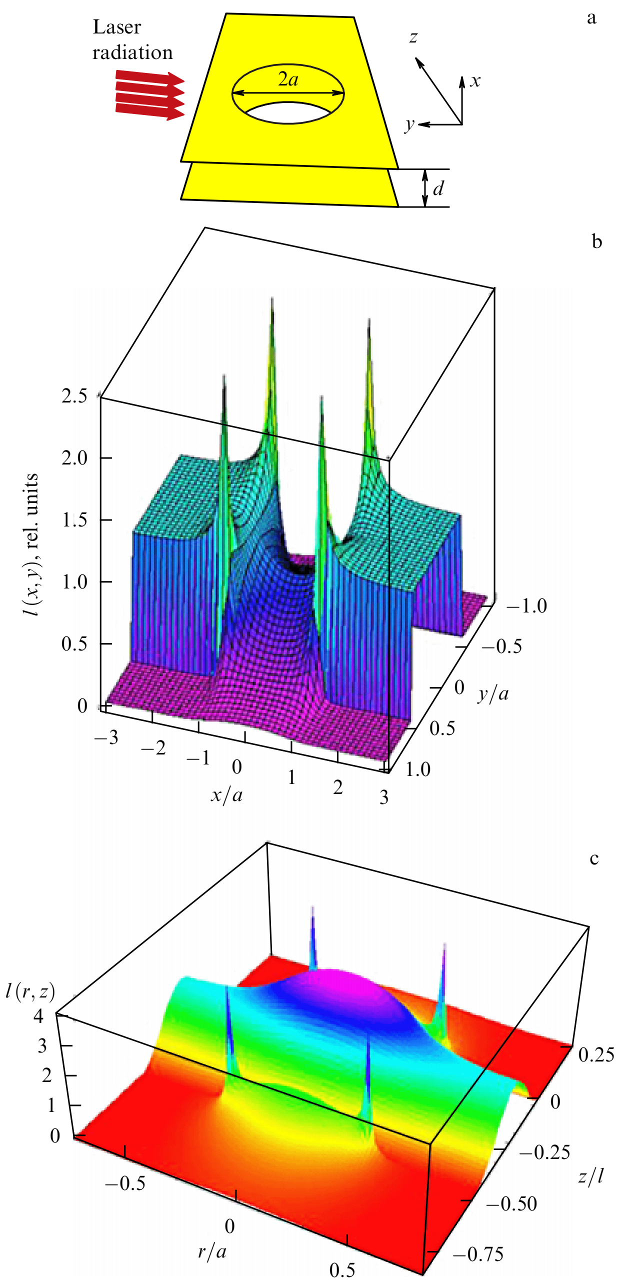

Figure 4. Three-dimensional nanolocalization of light. (a) Scheme for obtaining a spatially localized light nanofield: two conducting screens with a distance d between their planes, which is of the order of or smaller than the light wavelength, make up a planar two-dimensional waveguide for laser radiation injection into it from one side. (b) Energy density distribution for the electric field of the 'photon hole'. (c) Energy density distribution for the electric field of the 'photon dot'.

When the conducting screens have two small coaxial holes of radius a significantly smaller than the input radiation wavelength, $a \ll \lambda$, the radiation can hardly escape through these holes. However, the radiation traveling along the waveguide would be strongly modified in the vicinity of the holes. Near the holes there actually occurs field lowering in the domain with a characteristic spatial dimension of the order of the hole diameter, i.e., substantially smaller than the radiation wavelength. The volume of this domain is $V \ll \lambda^3$. Field modification near the holes depends on the polarization of the laser field inside the waveguide. Figure 4b demonstrates the energy density distribution for radiation with the electric field vector perpendicular to the plane of the waveguide. Field modification of this kind was termed a 'photon hole' [34]. One can see that in the vicinity of the holes there forms a photon hole whose characteristic dimensions are specified by the hole diameters and the waveguide thickness.

Figure 4c depicts the field intensity distribution near the hole of a planar waveguide and inside the waveguide, when the electric field vector of laser radiation is parallel to the waveguide plane, the waveguide thickness is equal to half the wavelength, and the hole radius $a = \lambda/2$. As is evident from the figure, the field decays quite rapidly outside of the waveguide in the direction perpendicular to the waveguide plane and peaks in the middle of the waveguide, i.e., a 'photon dot' forms. The characteristic volume of such a photon dot is also smaller than λ^3. The sharp field intensity peaks at the aperture edge are attributable to the assumption that the waveguide walls possess infinite conductivity. It is significant that the height of the maximum of the field in the middle of the holes is now twice the height of the maximum in the case of one hole. This circumstance, which is due to the constructive interference of the fields scattered by the holes, permits using lower fields than in the case of a single hole.

The photon dot and the photon hole may be employed to focus atomic beams by the gradient force which is proportional to the intensity of the electric field [34, 36]. For a positive detuning of laser radiation frequency relative to the atomic radiation frequency, the atom is forced into the lower-field domain; for a negative detuning, the atom is pulled into the higher-field domain.

2.3 Atom nanopen lithography

Nanopen lithography is a way of constructing arbitrary structures on a surface, which is similar to the deposition of ink lines on paper using a pointed pen. To draw such lines on a nanoscale calls for a nanopen. In the first nanopens (developed at Northwestern University, USA), atomic-force microscope probes were used as the pen. In this nanolithography technique, the reservoir of atom-ink is at the tip of the scanning probe which travels along the surface to leave behind it atom-sized lines. A serious disadvantage of the method is the long duration of the nanostructure fabrication procedure.

A nanometer hole in a screen on which an atomic beam is incident makes up an *atom pen* [37]. Atoms transmitted through the nanohole produce a nanospot on the surface behind the screen. By transferring the nanohole it is possible to produce nanostructures of arbitrary profile. The number of holes may be very large ($\sim 10^7$), which permits realizing parallel atom nanofabrication. Figure 5 shows one of the nanostructures made of Cr atoms with the aid of an atom nanopen [37]. The half-width of these nanostructures equals 170 nm.

2.4 Atom pinhole camera with a nanometer resolution

Despite the multiplicity of suggestions concerning the focusing of atomic beams by laser radiation, experimentally this remains a difficult problem. The main difficulty consists in the formation of an electromagnetic field – atom interaction potential which would be close in properties to a 'perfect' lens for atoms.

We experimentally realized [38] for the first time a different approach to the problems of focusing and constructing images in atom optics, which relies on the well-known idea of a pinhole camera employed both in light optics and in

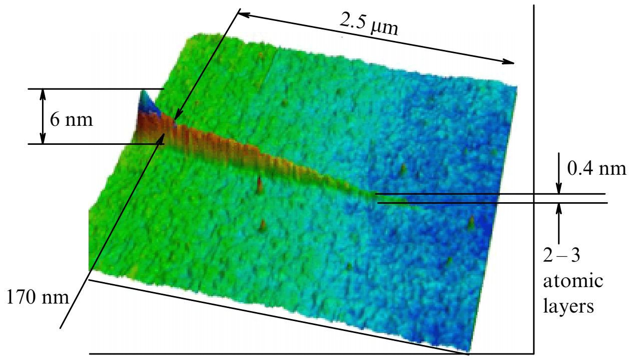

Figure 5. Nanostructure of Cr atoms made in the form of a varied-height strip with the help of an atom nanopen. The nanostructure half-width is 170 nm [37].

modern experimental physics when the focusing potential formation involves difficulties [39]. A pinhole camera in optics is a lens-free camera. The image-forming light passes through a hole which has to be small enough to produce a sharp image.

Figure 6 illustrates the schematic diagram of the experiment with an atom pinhole camera. An atomic beam is transmitted through a set of holes in a metallic mask to form, by analogy with optics, a 'luminous object' with a prescribed geometry. The atoms transmitted through the holes in the mask travel in a vacuum along rectilinear trajectories, like light beams, to arrive at a thin film with a large number of cone-shaped openings, which is located at a distance L from the mask. Each opening in the film is a pinhole camera for atoms, which forms an individual image of the object on the surface of a substrate positioned at a short distance l behind the film. In this geometry, a set of object images demagnified by about a factor of $m = L/l$ is produced on the substrate by the atoms deposited on its surface. In experiment, the object-forming mask was placed in the immediate vicinity of the source of atoms. For a thin film with openings, advantage was taken of a 5-μm thick track membrane with an asymmetric structure [40] and opening diameters $d = 20 - 1000$ nm.

In the experiment under discussion, every pinhole camera produces an image 'spot' of radius $a = (d/2)(1 + 1/m)$ in the plane of the substrate surface. The geometrical atom optics approximation is realized under the following limitation on

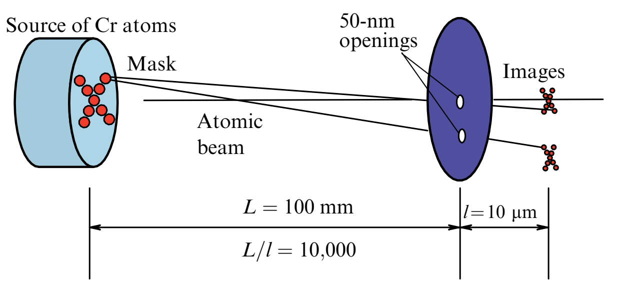

Figure 6. Schematics of a pinhole camera for atoms. A beam of Cr atoms transmitted through a set of holes in a metallic mask forms a 'luminous object' with a prescribed geometry. The atoms pass through the holes in the mask and travel along rectilinear trajectories to arrive at a thin film with openings. Each opening in the film is a pinhole camera for atoms and forms an inverted object image on a substrate.

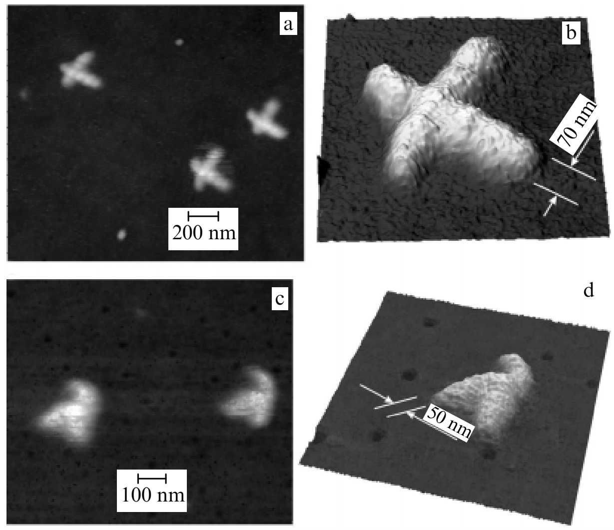

Figure 7. Nanostructures of Cr atoms on a glass surface, produced with an atom pinhole camera and a mask-object in the form of a cross: the areas of substrate portions are (a) 2×2 μm, and (b) 800×800 nm. Nanostructures of Cr atoms for a mask-object in the form of the letter λ: the areas of substrate portions are (c) 1×1 μm, and (d) 500×500 nm.

the de Broglie wavelength λ_{dB}: $1.22\,(\lambda_{\mathrm{dB}}/d)\, l \ll d(1 + 1/m)$. In this case, the image, which is the inverted copy of the object demagnified by a factor m, has a resolution of the order of d, which permits producing nanometer-sized structures.

In the experiment, the average speed of Cr atoms in the beam was equal to about 900 m s^{-1}, which corresponds to the de Broglie wavelength $\lambda_{\mathrm{dB}} = 0.08$ Å. The diffraction of atoms by the atom pinhole camera may be neglected for this wavelength.

Figures 7a and 7b display the Cr atomic nanostructures on a glass surface, which were obtained using an atom pinhole camera and a 'mask-object' in the form of a cross. Shown are portions of the substrate with areas of 2×2 μm (Fig. 7a) and 800×800 nm (Fig. 7b). The nanostructures were studied employing a scanning atomic-force microscope. Along with nearly complete images of the cross, the picture also presents structures that are images of only its part. This takes place due to a partial blocking of the atoms that form the image of the cross, which arises from the nonparallelism of the axes of different openings in the track membrane.

Figure 7b exhibits the detailed, most complete image of one of the crosses. The nanostructure base width is about 110 nm, which corresponds to the rectilinear passage of the beam's atoms through the openings in the pinhole cameras, and it is determined by the sum of their inlet diameter $d =$ 50 nm and the mask image diameter $d = 0.5$ mm$/8000 =$ 62 nm. The half-width of the nanostructure is equal to 70 nm.

Figures 7c and 7d give the results of an experiment involving the use of a mask in the form of the Greek letter lambda. The dimensions of this mask were smaller than the 'cross' type mask, with a consequential increase in the fraction of complete nonvignetted images. One can see from the figure that the half-width of the nanostructures produced is equal to 50 nm.

Figure 8 shows a nanostructure fabricated from Cr atoms in the form of the letter lambda, which is the symbol of the Institute of Spectroscopy of the Russian Academy of Sciences.

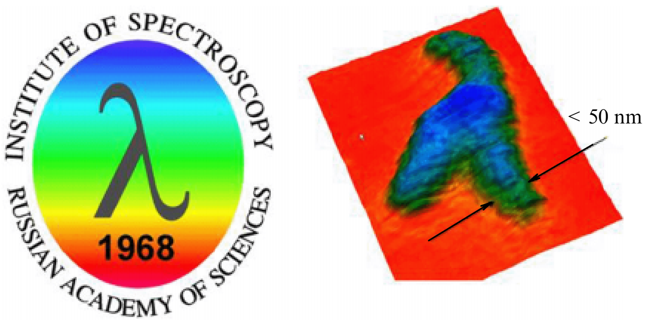

Figure 8. Cr atomic nanostructure in the form of the letter lambda, which is the symbol of the Institute of Spectroscopy of the Russian Academy of Sciences.

3. Summary

We have studied 'bottom up' approaches to nanotechnology, whereby the nanoobject being fabricated is assembled of individual atoms, molecules, biological cells, etc. The opportunity of realizing bottom up technology opened up with the development of probe microscopy techniques. However, the methods reliant on the use of scanning probes hold little attraction from the practical point of view, because they are characterized by a low productivity and a high cost. An alternative approach to bottom up nanotechnology is guided by atom optics. In this technique, the internal or external degrees of freedom of individual atoms are controlled by laser fields with nanometer precision, making it possible to produce surface structures at the nanometer scale.

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DOI: 10.1070/PU2007v050n07ABEH006323

Properties and nanotechnological applications of nanotubes

Yu E Lozovik, A M Popov

1. Introduction

The last decade has seen considerable progress in nanomechanics. In particular, the feasibility of manipulating nanometer-sized objects has been demonstrated [1] and basic designs for nanoelectromechanical systems (NEMSs) which can realize controllable motion of nanoobjects have been considered [2]. The search for nanoobjects that may be employed as the movable elements of NEMSs is currently a topical problem. The possibility of arbitrary [3, 4] relative motion of walls in multi-walled carbon nanotubes [7] that is controllable with an atomic-force microscope [5, 6] and the extraordinary elastic properties of carbon nanotube walls [8–12] make them challenging candidates for NEMS elements. Several nanomechanisms have been suggested, which are based on the relative sliding or rotation of nanotube walls: a nanobearing [13], a nanogear [14], a nanoswitch [15], a nanorelay [16, 17], a gigahertz oscillator [18, 19], and a Brownian nanomotor [20, 21]. The unique electronic properties of carbon nanotubes [22] find use in experimentally realized electronic nanodevices like nanotransistors [23], nanodiodes [24], current nanomodulators [25], etc. Furthermore, nanomotors reliant on the relative rotation of carbon nanotube walls have been made recently [26, 27]. In the nanoresistor, nanorelay, and nanomotor mentioned above, the nanotube walls are simultaneously movable NEMS elements and elements of an electric circuit. This family of carbon nanotube applications in NEMSs embraced a new unique and promising application: specifically, it was shown that a double-walled carbon nanotube (DWNT) could be a pair with an effective 'screw thread' [28–32]. In this connection, basic designs were proposed for NEMSs based on carbon nanotubes whose structure comprises a 'nanobolt–nanonut' pair: a 'nanodrill' for nanolocal surface