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Parallel Fabrication of Atomic Nanostructures

V. I. Balykin[a], P. A. Borisov[a], V. S. Letokhov[a], P. N. Melentiev[a], S. N. Rudnev[a], A. P. Cherkun[a], A. P. Akimenko[b], P. Yu. Apel'[b], and V. A. Skuratov[b]

[a] *Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow oblast, 142190 Russia*
[b] *Joint Institute for Nuclear Research, ul. Zholio-Kyuri 6, Dubna, Moscow oblast, 141980 Russia*
e-mail: akimenko@lnr.jinr.ru

Abstract—A new approach to fabrication of atomic nanostructures for atomic nanooptics is reported, which is based on the use of one-, two-, and three-dimensional spatial localization of laser fields at the nanoscale level, and fabrication of atomic nanostructures on a surface is demonstrated.

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INTRODUCTION

Currently, microelectronic semiconductor devices are fabricated mainly by photolithography. Fabrication of structures with smaller sizes is a technological problem of practical importance and fundamental interest, since structures with sizes of about 10 nm can be considered as a bridge between the classical and quantum worlds [1]. There are several approaches to fabrication of nanostructures with sizes of several tens of nanometers; each of them has a number of advantages and drawbacks. In particular, the difficulties in further development of approved methods are well known: (i) conventional photolithography has a diffraction limit of about 100 nm, (ii) lithography based on charged-particle beams meets problems related to commercial production of structures and a significant role of Coulomb repulsion, (iii) scanning probes have a low output [2], and (iv) self-assembling fabrication is not an universal process.

1. ATOMIC OPTICS

An alternative approach for nanotechnology is atomic optics, i.e., optics of material particles (as well as electron, ion, and neutron optics); it deals with problems of formation and control of ensembles and beams of neutral atoms and questions related to their application. The term "atomic optics" is similar to the terms "light optics" or "photon optics".

During the last 10–15 years, atomic optics has developed into an important field of atomic, molecular, and optical physics, which contributes to different technologies [3–10]. An important direction of atomic optics is the development of basic elements, similar to the well-known elements of conventional light optics. Among many applications of atomic optical elements, atomic lithography is potentially important for micro- and nanofabrication of material structures. In atomic lithography, the internal and (or) external degrees of freedom of individual atoms are controlled with nanoscale accuracy by external electromagnetic fields, thus making it possible to form nanostructures on a surface. The possibility of locating atoms on a surface with atomic accuracy by means of atomic optics was noted for the first time by Balykin and Letokhov [11, 12].

Let us consider the main nanofabrication methods that are used in atomic optics.

1.1. Atomic Fabrication of Nanostructures on the Basis of Traveling and Standing Light Waves

In recent years, a number of suggestions have been made and experiments have been performed on nanofabrication of atomic structures by focused atomic beams, using traveling and standing light waves [11–26]. On the whole, there are two basic concepts about focusing atoms by laser light of traveling and standing light waves. One of them is focusing of atoms by a single laser beam [13, 14]. This method was based on the so-called hollow beams [11, 12, 15, 16]. When atoms propagate in a laser beam, they are focused by the gradient force of light pressure. The distribution of atomic density in the focal plane of such an atomic lens has a width of about one angstrom, i.e., is comparable with the atomic size [11, 12].

The other concept of nanofabrication is focusing of atoms by a standing laser wave [17–26]. This method is of particular interest for fabricating periodic submicron structures. Deposition of atomic structures by a standing light wave was demonstrated for the first time by the example of sodium atoms [17, 21].

1.2. Atomic Fabrication of Nanostructures on the Basis of Laser Nanofields

Atomic optics based on traveling and standing laser fields has a number of limitations, fundamental and technical, which arise due to the spatial nonlocality of laser light fields. The nonlocality of a laser light field leads to nonlocality of atomic optics elements. A consequence is the imperfection of atomic optics elements: aberrations of atomic lenses, low diffraction efficiency of atomic waves, limitations on the contrast of interference fringes in atomic interferometers, etc.

From general physical considerations, it is clear that the use of spatially localized atom–field interaction potentials is preferred for constructing atomic optics elements, in particular, atomic lenses. To date, only three types of laser fields that are sufficiently well localized in space are known: (i) the surface light wave arising at total internal reflection of light (one-dimensional light localization), (ii) the light field arising at light diffraction at structures with sizes smaller than the light wavelength (two-dimensional light localization), (iii) the light field localized in partially open waveguides: "photon dot" and "photon hole" (three-dimensional light localization). The two latter types of laser nanofields are applied in atomic lithography.

1.2.1. Atomic lens based on the Bethe hole

The best known example of two-dimensional light localization is the Bethe hole: a hole in a thin conducting plate with a diameter smaller than the radiation wavelength [27–30]. The possibility of using such a nanolocalized field in problems related to focusing atomic beams was investigated in [31–34]. It was shown in [32–34, 36] that an array of near-field microlenses can be used to fabricate micro- and nanostructures on surfaces.

In an atomic lens based on the Bethe hole, laser light illuminates a conducting plate with a hole having a diameter smaller than the light wavelength. The field on the upper side of the plate consists of a traveling wave and the near-field component. The latter has the following remarkable features: (i) the near-field component in the immediate vicinity of the hole has the same order of magnitude as the incident field; (ii) the near-field component decays beyond the conducting plate at a characteristic length of the same order of magnitude as the hole diameter; and (iii) the near-field component has axial symmetry in the plane parallel to the plate, and its value changes approximately as a square of the distance from the axis to the hole. The exact formal solution to the problem of diffraction of a plane wave on a round aperture in an infinitely thin metal plate was obtained in [27–30].

Analysis of near-field atomic focusing [32–34, 36] showed that effective focusing can be obtained for a relatively slow atomic beam. At high atomic velocities, the short interaction time limits the dipole interaction, whereas at low velocities diffraction limits the atomic beam size in the focus. The minimum size of the focal spot is determined by a number of factors, which include spherical aberrations, chromatic aberrations, diffraction of atoms at the aperture hole, finite divergence of the incident atomic beam, interaction of atoms with each other (when the density is sufficiently high), and spontaneous emission. The size of the focal spot, with due regard to the above-mentioned factors, is 0.1 of the optical wavelength.

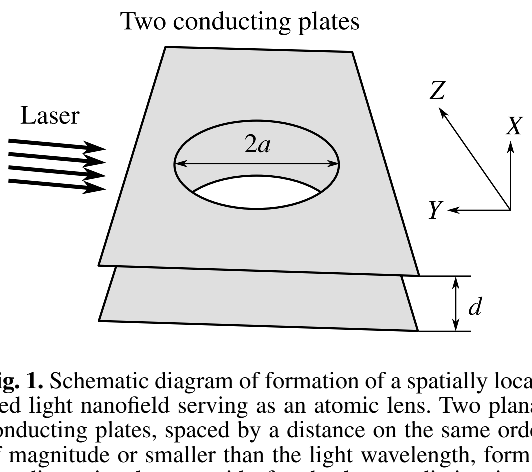

Fig. 1. Schematic diagram of formation of a spatially localized light nanofield serving as an atomic lens. Two planar conducting plates, spaced by a distance on the same order of magnitude or smaller than the light wavelength, form a two-dimensional waveguide for the laser radiation introduced into it from aside.

1.2.2. Atomic lens based on a photon dot and a photon hole

A significant drawback of the atomic microlens in the form of a field localized near a single hole is the intimate connection of this field with the field of the corresponding standing wave. Motion of an atom in this region may be accompanied by processes of spontaneous decay, which in many cases are undesirable for atomic lithography problems. We investigated new types of spatially localized laser light fields with a characteristic spatial size in the nanoscale range, which are free from the noted drawback [34, 35].

The scheme for obtaining such a spatially localized light nanofield [34, 35] is shown in Fig. 1. Two planar conducting plates spaced by a distance of the same order of magnitude or smaller than the light wavelength, form a planar two-dimensional waveguide for laser radiation introduced into it from aside. It is known that, for a waveguide composed of two parallel ideally conducting planes, there is a solution to the Maxwell equation that allows propagation of radiation through the waveguide at its arbitrarily small thickness d, including the thicknesses much smaller than the radiation wavelength.

If two small coaxial holes with a radius a much smaller than the wavelength of introduced radiation ($a \ll \lambda$) are formed in the conducting plate, the radiation almost does not escape through these holes; however, the radiation propagating along the waveguide will be significantly modified near each hole. The volume of this region $V \ll \lambda^3$. The field modification near the holes depends on the laser field polarization in the waveguide. For radiation with the electric field vector directed perpendicularly to the waveguide plane, the energy density distribution has a minimum in the vicinity of the holes, with a characteristic size determined by the hole size and the waveguide thickness. The field modification of such kind is referred to as the photon hole [34].

Figure 2 shows the field-intensity distribution near a hole in a planar waveguide and inside the waveguide for the case where the laser electric field vector is parallel to the waveguide plane, the waveguide thickness is equal to the half-wavelength, and the hole radius $a = \lambda/2$. It can be seen in Fig. 2 that the field decreases fairly rapidly beyond the waveguide in the direction perpendicular to the waveguide plane, and is maximum in the middle of the waveguide, i.e., a photon dot is formed. The characteristic volume of such a photon dot is also smaller than λ^3. It is noteworthy that the maximum value exceeds the corresponding value for the case of a single hole by a factor of 2. Photon dots and holes can be used to focus atomic beams by a gradient force, which is proportional to the electric field strength [34, 35]. At a positive detuning of the laser radiation frequency from the atomic emission frequency, the atom is pushed off into the region of weaker fields, whereas in the case of negative frequency detuning, the atom is pulled into the region of stronger fields.

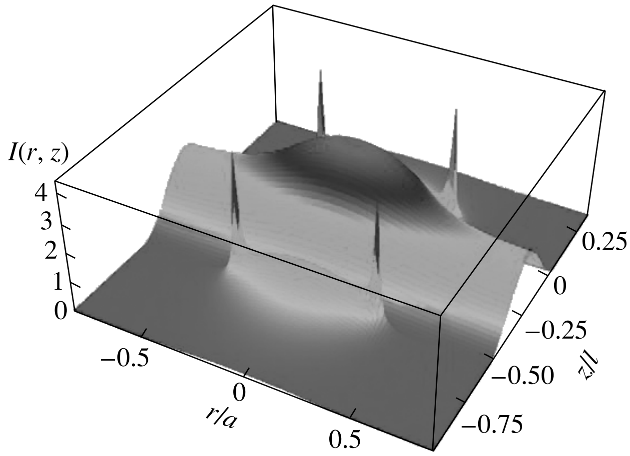

Fig. 2. Distribution of the energy density of the electric field of the photon dot formed in a two-dimensional waveguide (see Fig. 1).

1.3. Atomic Nanopen Lithography

Nanopen lithography is a technique for forming arbitrary structures on a surface, which is analogous to drawing lines on a paper with ink by a pen. To draw such a line at the nanoscale level, it is necessary to develop a nanopen. The first nanopens were based of probes for an atomic force microscope. In this nanolithography method, the reservoir of atoms (ink) is stored at the tip of the scanning probe, which moves along the surface, "drawing" a line of atomic size. A serious drawback of this method is the long nanofabrication time.

In [37], we proposed and implemented an atomic pen in the form of a nanoscale hole in a plate onto which an atomic beam is incident. The number of holes can be very large ($\sim 10^7$), as a result of which parallel atomic nanofabrication can be performed. Displacement of a nanohole allows one to develop nanostructures with an arbitrary profile. We demonstrated the possibility of creating nanostructures from Cr, Ag, and In atoms using an atomic nanopen [37]. The width of the nanostructures formed at half-maximum is 170 nm.

1.4. Atomic Obscure Camera with a Nanoscale Resolution

Despite a large number of proposed methods for focusing atomic beams by laser radiation and constructing images, this problem remains experimentally difficult. The main difficulty is the fabrication of the atom–field interaction potential with properties similar to those of the "ideal" lens for atoms.

In [38], we experimentally implemented for the first time another approach to the problem of focusing and constructing images in atomic optics, which is based on the concept of an obscure camera; the latter is used both in light optics and in modern experimental physics when it is difficult to form a focusing potential [39]. In optics, an obscure camera is a camera without a lens. Light, forming an image, passes through a small hole. To obtain a fairly clear image, the aperture of such a camera should be a hole of small diameter.

In an atomic "obscure camera", an atomic beam is transmitted through an array of holes in a metal mask, thus forming, by analogy with optics, a "luminous object" of specified geometry. The atoms transmitted through the holes in the mask, propagating in vacuum over straight-line trajectories (like light rays), arrive at a thin film located at a distance L from the mask with a large number of holes. Each hole of the film serves as an obscure camera for atoms, forming an individual image of the "object" on the surface of a substrate, which is located at a small distances l behind the film. In this geometry, a set of object images, decreased approximately by a factor of $m = L/l$, is formed on the substrate. The metal mask forming the object is located in the immediate vicinity of the atomic source. As a thin film with holes, we used a track membrane with asymmetric structure [40], having a thickness of 5 μm and the hole diameter $d = 20$–1000 nm.

In the experiment, the average velocity of beam atoms was about 900 m s^{-1}, which corresponds to the de Broglie wavelength $\lambda_{dB} = 0.08$ Å. At such a de Broglie wavelength, the approximation of geometric atomic optics is valid, and diffraction of atoms in the atomic obscure camera can be neglected.

Figure 3 shows nanostructures formed of Cr atoms on the glass surface using an atomic obscure camera

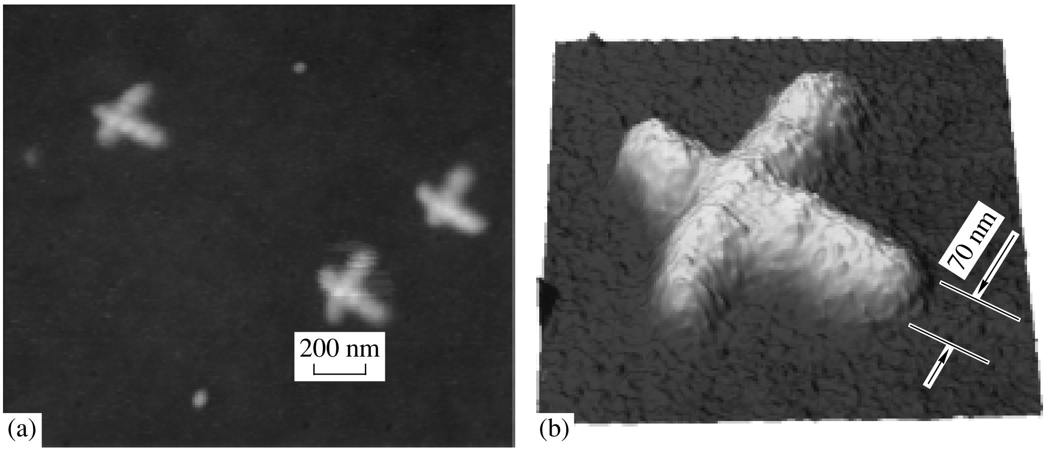

Fig. 3. Nanostructures formed of Cr atoms on the glass surface, obtained with an atomic obscure camera and an object mask in the form of a cross. Substrate portions with areas of (a) 2×2 μm and (b) 800×800 nm are shown.

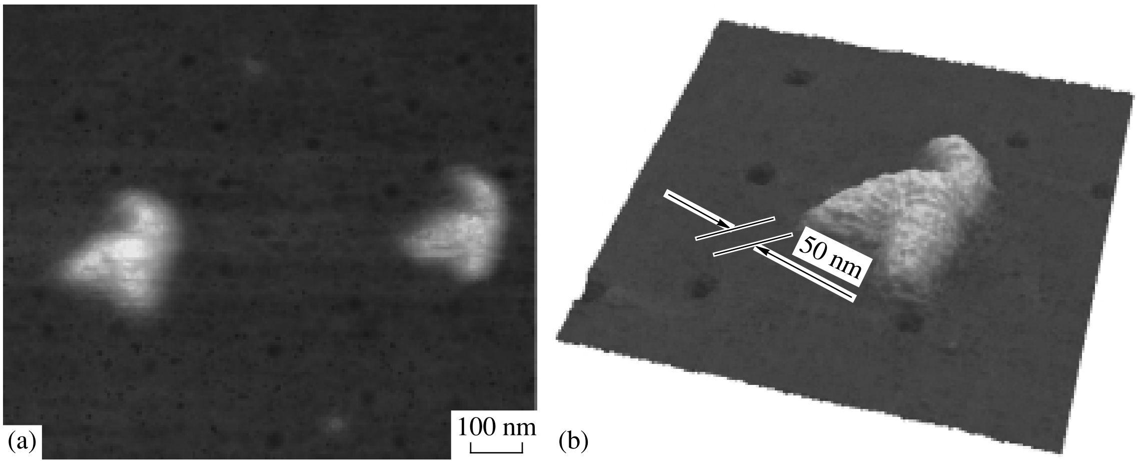

Fig. 4. Nanostructures formed of Cr atoms on the glass surface, obtained with an atomic obscure camera and an object mask in the form of the Greek letter λ. Substrate portions with areas of (a) 1×1 μm and (b) 500×500 nm are shown.

and an object mask in the form of a cross. Substrate portions with areas of (a) 2×2 μm and (b) 800×800 nm are shown. The nanostructures were investigated with a scanning atomic force microscope. Figure 3b shows a detailed image of one of the crosses. The width at the half-height of the nanostructure is 70 nm; this value corresponds to the straight-line transmission of beam atoms through holes in the obscure camera and is determined by the sum of the input diameter $d = 50$ nm and the diameter of the mask image, $d_0 = 0.5$ mm/8000 = 62 nm.

Figure 4 shows the experimental results obtained with a mask in the form of the Greek letter λ. The sizes of this mask are smaller than the cross mask, as a result of which the images are smaller in size. It can be seen in Fig. 4 that the width of the formed nanostructures at half-height is 50 nm.

CONCLUSIONS

Nanotechnological approaches based on the methods of atomic optics have been investigated. In these methods, the internal or external degrees of freedom of individual atoms are controlled with nanoscale accuracy by laser fields, thus making it possible to form structures on a surface with nanoscale precision.

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