ATOM NANO-OPTICS AND NANO-LITHOGRAPHY

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1. Introduction

Semiconductor devices are currently constructed on a microscopic scale, predominately using optical lithography. The fabrication of structures at scales smaller than the current limits is a technological goal of great practical, but also fundamental interest: material structures with dimensions in the 10 nm range represent a bridge between the classical and the quantum mechanical world. In practice, it is desirable to have the ability to build any nanostructures with atomic precision using any atomic species. To date, no single approach meets this demand. Rather, there are a number of techniques, each of them possessing some advantages and having some drawbacks. In particular, there are known difficulties for further development of well-known techniques: Conventional optical lithography is diffraction limited down to 100 nm; charged particle beam lithography suffers from the serial nature of patterning and Coulomb repulsion; scanning probes, as they manipulate single atoms, are generally too slow; and self-assembled fabrication still requires a better understanding of the physical processes. Micro and nanofabrication of material structures is denoted generically as atom lithography.

We report here on the new approaches in atom lithography that is based on the use of (1) the spatially on nanometer scale localized laser fields; (2) the atom nanopencil; (3) the atom pinhole camera, and (4) the laser induced quantum atom adsorption on a surface.

2. Nanometer scale localized laser fields

The ultimate goal in the field of atom nano-optics is the formation of nanometer-sized ensembles and beams of neutral atoms. It is known that laser fields capable of forming such atomic ensembles must be well localized. Standing light waves - the best known laser fields - are finding widespread use in atom optics. The first application of standing light waves in atom nano-optics was the localization of atoms in a nanometer-sized space and their placement in channels. The idea of channeling atoms in a standing light wave has led to the development of techniques of atom lithography that allow periodic one- and two-dimensional structures to be produced on a surface.[1] On the basis of general physical considerations, it is evident that the use of spatially localized fields (and, accordingly, spatially localized atomic potentials) can offer new possibilities for the construction of atom-optical elements. To date, we have knowledge of only two types of laser fields that are well enough localized in space to make this possible: surface (evanescent) light waves and light that arises in the vicinity of structures with a characteristic size of less than the wavelength.

Evanescent waves find widespread use in atom optics for the reflection, localization and cooling of atoms. A drawback of evanescent waves is that they are localized exclusively on a 2D surface. The three dimensional localized light field is that which results after diffraction by an aperture the size of which is small in comparison to the wavelength of light. In this case, a local 3D maximum of field intensity is formed near the aperture. The magnitude of the maximum is governed mainly by the size of the aperture. A substantial drawback of the field structures considered above is the accompanying standing or traveling light wave: when atoms move in a standing light wave they can undergo spontaneous decay processes that, in many cases, undesirable.

The light nanofield configurations that are free from the above-mentioned shortcomings are the following.[2] Two plane conductive plates spaced a distance d of the order of or smaller than the wavelength of light apart form a plane waveguide for the laser radiation coupled into it from one side. If the electric field strength vector of the laser radiation is normal to the plane of the waveguide, the radiation can propagate through the

waveguide, no matter how thin it is. Now let two small coaxial apertures be made in the conductive screens that form the waveguide. If the diameters a of these apertures are smaller than the wavelength of the radiation coupled into the waveguide, little radiation escapes from the waveguide through the apertures, but the light field near them is strongly modified. Figure 1 shows the light field intensity distribution near the apertures inside and outside the waveguide when the thickness of the waveguide is equal to the radius of the apertures. As can be seen in Fig. 1, there is a light field intensity minimum in the direction normal to the plane of the waveguide. Such a light field configuration can be called as a photon hole. Its characteristic size is determined by the size of the apertures, the thickness of the waveguide and its volume $V \sim a^2 d \ll \lambda^3$. The sharp field intensity peaks near the aperture edges are caused by the hypothetic infinite conductivity of the waveguide walls. In waveguides with walls of finite conductivity, the amplitude of the field intensity peaks is not manifested in such a pronounced manner.

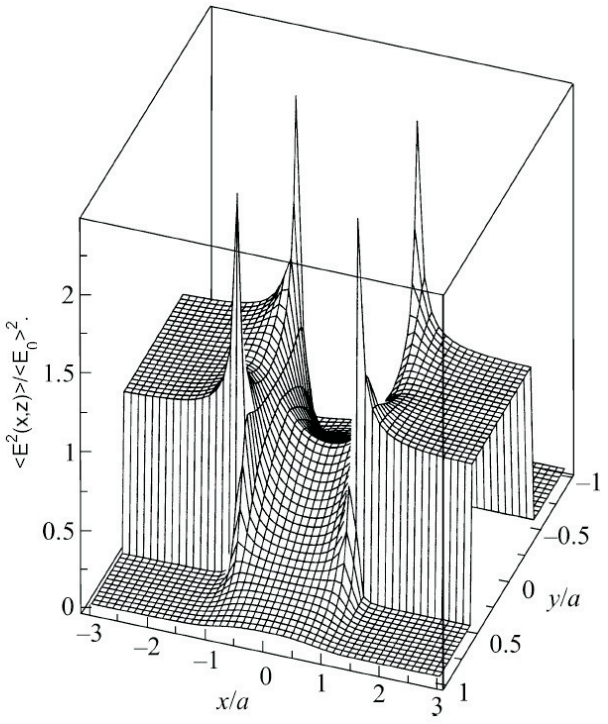

Fig. 1. Electromagnetic-field intensity for a photon hole.

If two conductive screens with coaxial apertures are spaced a distance of $d = \lambda/2$ apart and the electric field strength vector is parallel to the waveguide plane than the intensity distribution in such a light field is different than in the previous case, Fig. 2. As can be seen, the field drops off rapidly outside the waveguide in the direction normal to the waveguide and has its maximum at the center of the waveguide. This maximum is caused by the constructive interference of the fields scattered by the apertures. Such a light field configuration can be called as a photon dot. The maximum intensity at the photon dot is twice as high as the field intensity in the absence of apertures.

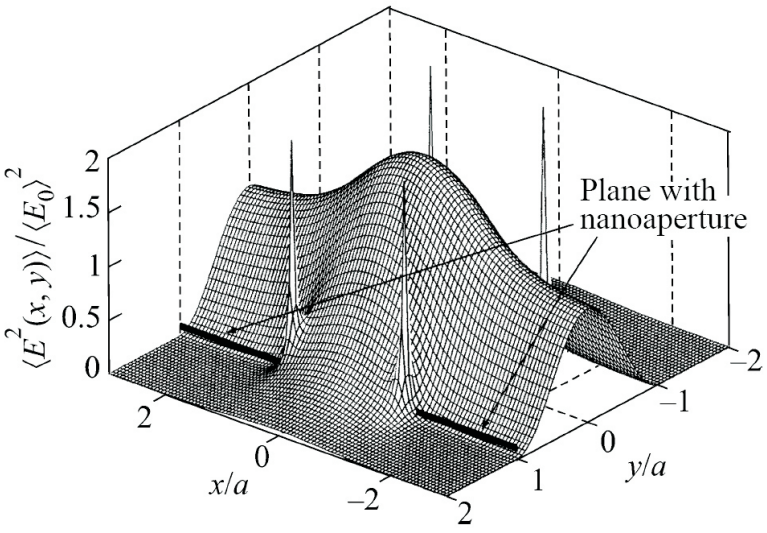

Fig. 2. Electromagnetic-field intensity for a photon hole.

The characteristic size of a photon dot or a photon hole is in the nanometer region, which allows for nanometer-sized atomic ensembles to be formed. Let us consider as an example two possible uses for photon dots and photon holes: the focusing and localization of atoms. When an atom is exposed to laser light, electric field of the laser light induces in the atom an oscillating dipole moment. If the light field amplitude at the atom position is spatially nonuniform, a gradient force on an atom develops. It is precisely the gradient force that is used to modify the trajectory of the atoms. When the detuning of the laser radiation frequency relative to the atomic transition

frequency is positive, an atom in the laser light configuration is drawn into the weak field region. In the case of a photon hole, the nanometer- sized weak field region is surrounded by the strong field inside the waveguide; if the light field frequency detuning is positive, the atoms that fly through the apertures in the waveguide walls will be attracted to the axis of the system-in other words, they will be focused.

A photon dot draws atoms in negative frequency detuning and also provides focusing for the atomic beam that passes through the apertures in the waveguide walls. It has been shown[2,3] that an atomic beam can be focused to a spot of the order of the de Broglie wavelength, which for a thermal beam amounts to a few Angstroms.

The photon dot and photon hole light-field configurations have extreme points at which the gradient force is zero. Such light-field configurations are naturally considered as the possible atom trap configurations.[3] The photon dot light-field configuration is stable and is truly three dimensional, while in a photon hole light-field configurations either the axial or the radial motion of the atom will be infinite since no matter what the sign of the frequency detuning. The extreme photon hole point is a saddle point. A number of schemes can be used to make the atomic motion in the photon hole region finite. One is based on the use of frequency detuning that varies in sign and over time, making it possible to localize atoms dynamically in a way similar to the localization of ions in high-frequency electromagnetic traps.

3. Atom nanopencil

"Atom nanopencil" is an aperture in a thin material foil with a diameter ranging from 1 nm to 1 μm. As atomic beam passes through the aperture arbitrary patterns can be written by moving the aperture relative to a suitable substrate behind the foil. The aperture size defines the feature size of the written atom structures. A quantitative theoretical analysis shows that the van der Waals forces acting on the motion of atoms in the individual tapered channels of the aperture and the diffraction of the atomic wave to determine the final size of the deposited nanostructures.[5]

To produce a set of appropriate microholes for use as atom nanopencils, nanosieves have been built and characterized by using the atomic force microscope. The nanosieve has multiple openings of equal diameter, randomly situated in a dielectric foil. We have nanosieves with openings ranging from 40 nm to 1000 nm. In our experiment, a mica or glass substrate was positioned at a distance around 10 μm behind the nanosieves. By moving the nanosieves across an atomic beam, we are able to create atom nanostruc-

tures on the various substrates. Fig. 3 shows an example of such nanostructures: we create chromium nanolines with heights in the range of 1-10 nm, widths of 180 nm and lengths of 1200 nm. The total amount of nanolines produced in one process exceeds 10^7 and occupy an area of 2 x 2 mm on the substrate surface.

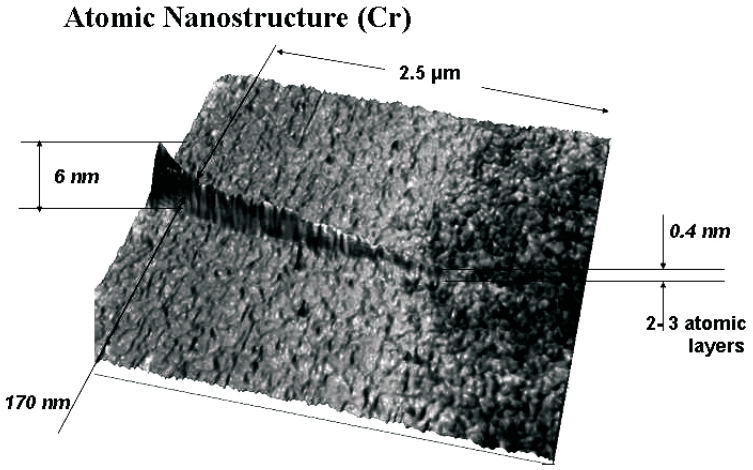

Fig. 3. Nanostructure of Cr atoms built with the atom nanopencil.

4. Atom pinhole camera

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 probing the surface at the atomic level, as well as for the creation of nanostructures on the surface. 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. 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 "optical pinhole camera". The pinhole camera in optics is a camera without lens. Light forming an image passes through a small hole. In our experiment with the atom pinhole camera the atomic beam passes through a set of holes in a metal mask and thereby forms, by analogy with optics, a "glowing" atomic object of a given geometry. The atoms pass through the mask, propagate in vacuum along

rectilinear trajectories, similar to light rays, and are incident on a pinhole. The great many pinholes were created in a thin plastic film.[6] As a thin film, we used a track membrane of an asymmetric structure.[6] The initial material for the track membrane was a Hostaphan RE5 (Hoechst AG) polyethylene terephthalate film 5-10 μm 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 was performed.

The thin film with a large number (n $=10^7 - 10^8$ cm^{-2}) of nanoholes (50 nm diameter) is placed at a distance of 90 mm from the mask. 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 $l = 5$ μm behind the film. Figgure 4(a) shows 2x2 μm surface section with the image 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.

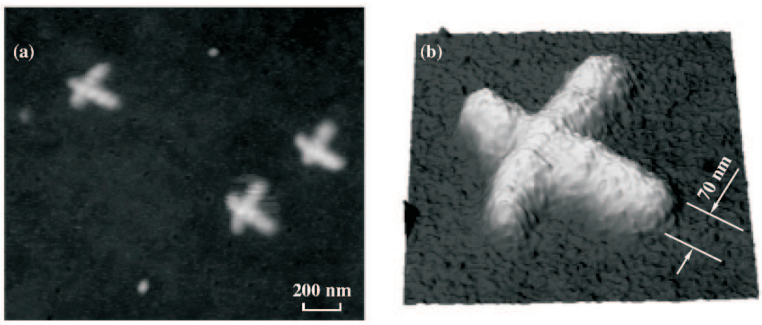

Fig. 4. Nanostructures of Cr atoms on the glass surface that are obtained using the pinhole camera and the "cross" atomic object. Surface sections of sizes (a) 2x2 μm and (b) 800 x 800 nm are shown. The nanostructures are measured by means of an atomic force microscope.

Figure 4(b) shows the detailed image of one of the crosses. As seen in the figure, the cross consists of partially resolved subnanostructures that are images of separate holes of the object mask. The width of the nanostructures is approximately equal to 70 nm, which well corresponds to the passage of

the atomic beam through the holes of pinhole cameras and is determined by the sum of the hole diameter $d = 50$ nm and the mask image diameter $d_0 = 0.5$ mm.

5. Laser-Induced Quantum Adsorption of Atoms on a Surface

The adsorption of an atom (molecule) on a surface is a natural process of the trapping of the atom (molecule) in a surface potential well. The probability of trapping of the particle on the surface is determined both by the electronic structures of the particle and surface and by the thermodynamics of the collision of particles with the surface. In addition to the general physical interest in the process of the adsorption of particles on the surface, the adsorption of particles underlies the modern industry of micro- and nanoelectronics based on the methods of molecular beam epitaxy or gas phase epitaxy. For this reason, the control of processes of the adsorption of particles on the surface are of both fundamental and large applied importance.

We propose a new mechanism of loading atoms into the surface potential well (i.e., their adsorption on a surface) and demonstrate the implementation of this scheme for Rb atoms adsorbed on the surface of a YAG crystal.[7,8] We also show the possibility of producing micro- and nanostructures of arbitrary shape that consist of atoms localized on the dielectric surface. The proposed mechanism of the loading of atoms into the surface trap is based on the energy-pooling effect, i.e., inelastic collision of two excited atoms followed by the transition of one of them to the ground state and the other one to the highly excited state.[9] The defect of the internal energy is compensated by the kinetic energy of the atoms. When the atomic collision occurs inside the surface potential well, an atom can be trapped in this potential well.

Figure 5a shows the scheme of the low-lying levels of the Rb atom. The $5^2P_{3/2}$ level of the Rb atom is populated due to the absorption of 780-nm laser light. The energy of the $5D$ level is close to the $5P + 5P$ asymptotic energy of the Rb_2 molecule and, therefore, can be populated owing to the energy-pooling collisions of excited atoms:

$$\mathrm{Rb}(5P) + \mathrm{Rb}(5P) + \Delta E \rightarrow \mathrm{Rb}(5D) + \mathrm{Rb}(5S), \qquad (1)$$

where $\Delta E = 93$ K is the difference between the total kinetic energies before and after collision (energy defect). As a result of collision process (1) of two atoms, one atom passes to the ground state and the other atom passes to

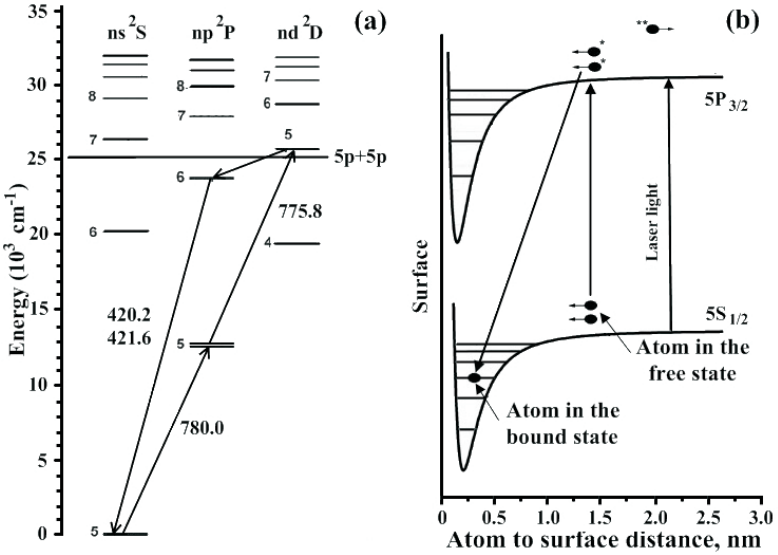

Fig. 5. (a) The energy level diagram for Rb atom. (b) The mechanism of loading of Rb atom in the surface trap.

the 5D excited state. The energy defect is compensated by the energy of the translational atomic motion; i.e., the kinetic energy of two atoms after collision event (1) decreases by 93 K. If the collision of two excited atoms occurs near the bottom of the surface potential well, the loss of the kinetic energy in the atomic collision can lead to the localization of an atom in the surface potential, i.e., to its laser induced adsorption, as schematically shown in Fig. 5b.

The quantum adsorption of Rb atoms is experimentally implemented on the surface a YAG crystal. The temperature of the surface can be varied from room temperature to 240 ^{0}C. Laser radiation is tuned to resonance with the D_2 line of Rb atom and a laser beam passing through and perpendicular to the surface. The laser beam diameter is varied between 0.5 and 2 mm and the maximum power of laser radiation is equal to 70 mW. The energy-pooling process is identified by detecting the blue fluorescence of Rb atoms (λ= 420.2 and 421.6 nm) from the laser beam.[9]

Laser induced quantum adsorption opens the possibility of creating atomic micro- and nanostructures with a given geometry on the dielectric surface. Such a possibility is illustrated in Fig. 6 on the example of creation of the three letters P, R, and L on the surface. Atomic structure

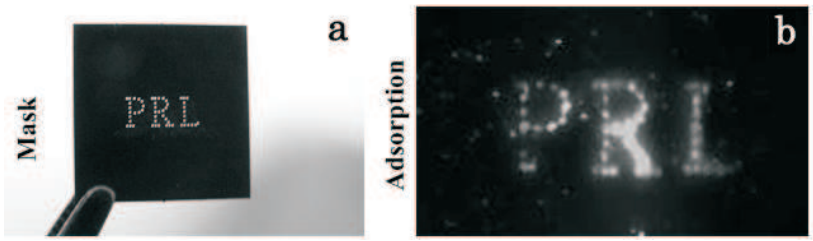

Fig. 6. (a) The mask consists of 35 holes in a thin metal foil. (b) The microstructure of Rb atoms in the form of three letters P R L that are obtained by the laser induced quantum adsorption.

of the shape PRL was produced in a following way: (1) 35 openings in a metal foil were done to produce a mask for these letters; (2) the mask was illuminated by the laser light; (3) the image of the mask was projected onto the surface and during the time interval $t = 5$ min were produced 35 microtraps on the surface reproducing the letters P, R, and L of size about 50 μm.

6. Acknowledgments

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