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A scientific session of the Physical Sciences Division of the Russian Academy of Sciences dedicated to the 40th anniversary of the Institute of Spectroscopy, RAS (ISAN) was held at ISAN on 8 October 2008. The following reports were presented at the session:

(1) **Balykin V I** (ISAN) "Atom optics and nanotechnology";

(2) **Ryabtsev A N, Churilov S S** (ISAN) "Spectroscopy of ionized atoms for astrophysics and nanotechnology";

(3) **Lozovik Yu E** (ISAN) "Strong correlations and new phases in a system of excitons and polaritons. A polariton laser";

(4) **Vinogradov E A, Mavrin B N, Novikova N N, Yakovlev V A** (ISAN) "Inverted optical phonons in ion-covalent crystals";

(5) **Mal'shukov A G** (ISAN) "Spin transport in semiconductor microstructures";

(6) **Dumesh B S, Potapov A V, Surin L A** (ISAN) "Spectroscopy of small helium clusters and 'nanoscopic' superfluidity: $He_N - CO$, $N = 2 - 20$...";

(7) **Naumov A V, Vainer Yu G** (ISAN) "Single molecules as spectral nanoprobes for the diagnostics of dynamic processes in solid media";

(8) **Kompanets O N** (ISAN), **Yevdokimov Yu M** (Engelhardt Institute of Molecular Biology, RAS) "Optical biosensors of genotoxicants based on DNA nanoconstructions and portable dichrometer."

A brief presentation of these reports, with the exception of report 5, is given below.

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Atom optics and nanotechnology

V I Balykin

1. Introduction

Atom optics (along with electron, ion, and neutron optics) is the optics of material particles and deals with the problems of forming ensembles and beams of neutral atoms and of controlling them, as well as with application issues. Atom optics became a discipline in its own right in the mid-1980s as an outcome of research on the interaction of laser radiation pressure forces with atoms executing translational motion. Despite its weakness in the case of ordinary light sources, the effect of light pressure was experimentally discovered by P Lebedev in Russia back in the late 19th century and was later confirmed by E Nichols and G Hull in the USA. The experimental proof that momentum is transferred from a photon to a free atom is credited to Frisch (1933), who observed the deflection of an atomic sodium beam under irradiation.

The advent of lasers provided researchers with a fundamentally new light source possessing a high spectral brightness, monochromaticity, and a high radiation directionality. When laser radiation came into use, light pressure ceased to be a barely observable effect and became an efficient means of influencing atomic motion. The progress in atom optics [1 – 3] is closely related to the development of laser cooling and neutral atom localization techniques [4 – 8]. The laser cooling of atoms and their spatial localization enable forming atomic ensembles and beams with desired parameters. Laser cooling allows decreasing the atomic temperature to only a millionth of a degree above absolute zero. At such temperatures, the de Broglie wavelength becomes comparable to the wavelength of light and the wave properties of atoms show up markedly. The localization of neutral atoms opens up the opportunity to operate both with single atoms localized to nanometer-scale precision [9, 10] and with macroscopic ensembles of cold atoms having a high phase density [11].

Laser methods of neutral atom cooling, which allowed a substantial increase of the de Broglie wavelength, gave birth to atom wave optics [12]. Using different configurations of laser light fields and mechanical micro- and nanostructures (zone plates, multislit stops, etc.), it has been possible to make coherent atomic beamsplitters, atom interferometers, waveguides, and, lastly, an analogue of the optical laser — the atom laser.

The potentials of atom optics are much broader than the potentials of the optics of other types of material particles (electrons and neutrons) due to the internal structure of atoms. For a temperature close to absolute zero, when the de Broglie wavelength becomes comparable to the interatomic distance, the behavior of an atomic ensemble becomes appreciably dependent on an internal quantum atomic characteristic, spin.

A striking difference between the behavior of fermions and bosons is observed at very low temperatures. In 1924, Bose and Einstein predicted the effect of condensation for Bose particles, known as the Bose–Einstein condensation. Atoms in a Bose–Einstein condensate (BEC) make up a new type of 'coherent matter.' The first atomic condensates were obtained by several groups of American physicists by laser and evaporative cooling techniques in 1995 [11]. A magnetic trap that retains BEC atoms is an analogue of the optical resonator for photons in an optical laser. The atoms may be 'released' from the magnetic trap in a certain direction and, like photons passing through a semitransparent mirror of the optical laser resonator, form a coherent directional beam similar to a laser beam. This device is referred to as an atom laser.

The keen interest in atom lasers stems from the prospect of harnessing coherent atomic beams in precision measuring instruments and sophisticated technologies in the preparation of atomic and molecular micro- and nanostructures [9, 10].

2. Methods of constructing the elements of atom optics

Although similar mathematical foundations underlie atom and light optics, their 'technical means' are different. Producing the tools of light optics relies on the techniques of grinding and polishing the surfaces of different reflective and transparent materials of the desired shape. In atom optics, the principal technical means are electromagnetic fields. The use of diverse configurations of laser light fields, static electric and magnetic fields, and material structures, including micro- and nanostructures, has enabled constructing the basic elements of atom optics that are analogous to the elements of conventional optics: atom lenses, mirrors, deflectors and modulators of atomic beams, coherent atomic beamsplitters, atom interferometers, and waveguides.

2.1 Material structures

In his classic monograph [13], Ramsey considered the specular reflection and diffraction of a molecular beam from the surface of a solid. For the specular reflection to occur, the following two conditions must be satisfied.

(1) The projection of the average height of surface irregularities on the molecular beam direction must be shorter than the de Broglie wavelength of the molecules. If δ is the average height of surface irregularities and φ is the grazing angle of beam incidence, this requirement can be expressed as

$$\delta \sin \varphi < \lambda_{\mathrm{dB}} . \qquad (1)$$

(2) The average on-surface residence time for molecules must be short. In this case, the quantum state of the reflected molecule is the same as for the incident one. The irregularities of mechanically well-polished surfaces are typically of the order of 10^{-5} cm, while the de Broglie wavelength of a hydrogen molecule at the temperature 300 K is of the order of 10^{-8} cm. Consequently, in accordance with inequality (1), the angle for the specular reflection to occur is $\varphi < 10^{-3}$ rad.

More than 50 year ago, Knauer and Stern [14] observed a 5% reflection of a hydrogen molecular beam from polished bronze for the grazing incidence angle $\varphi = 10^{-3}$ rad. Crystal cleavage surfaces are much smoother. Thermal vibrations of a crystal lattice limit the surface smoothness at the level of 10^{-8} cm. In this case, an atomic beam experiences specular reflection at the incidence angles $20^\circ - 30^\circ$. This was borne out in experiments [15] with He atoms and an LiF crystal. The temperature dependence of the specular reflection angle exhibits a strongly pronounced feature, which indicates a passage from the specular reflection of atoms to the diffuse one and testifies to the effect of thermal vibrations on the smoothness of the crystal surface. Experiments on the reflection of atoms from the surface of a condensed medium continue to attract the attention of researchers. We mention experiments involving the reflection of ^{4}He atoms from the surface of liquid ^{4}He [16] and of thermal Cs atoms from a polished glass surface [17].

The first experiment involving the observation of atomic diffraction by a crystal cleavage surface, which operated like a two-dimensional plane lattice, was performed by Stern [18]; a comprehensive investigation of this effect was set forth in Ref. [19]. Atomic diffraction by an artificial periodic structure (grooves in a membrane) with a much longer grating period was observed in Ref. [20].

The effect of the quantum reflection of ^{4}He and ^{3}He atomic beams from the surface of liquid helium in a vacuum was validly employed to focus atoms using a curved surface [21] and to focus He atoms using a zone plate [22].

Atom interferometry based on microstructures was realized in two elegant devices: Young's two-slit atom interferometer [23] and Michelson's atom interferometer [24].

2.2 Static electric and magnetic fields

Some elements of atom and molecule optics reliant on the interaction of spatially nonuniform magnetic and electric fields with the magnetic or electric dipole moments of particles have long been known and profitably used in experimental physics [13].

In the presence of a magnetic or electric field, an atom or a molecule shifts, with the displacement depending on the initial quantum state of the particle and the field magnitude (the Zeeman and Stark effects). In the adiabatic approximation (the fields change little in space and time, while the particles move relatively slowly), the internal state of the particles follows variations in the field strength or, to state it in different terms, the particles reside in the same quantum sublevel, whose energy W depends on the field strength.

In the adiabatic approximation, the center-of-mass motion of a neutral particle of mass M obeys the Schrödinger

equation for the wave function $\Psi(\mathbf{r}, t)$:

$$i\hbar \frac{\partial \Psi_i(\mathbf{r}, t)}{\partial t} = \left(-\frac{\hbar^2}{2M} \nabla^2 + W_i(\mathbf{r}) \right) \Psi_i(\mathbf{r}, t) , \quad (2)$$

where $W_i(\mathbf{r}, t)$ is the internal energy of the particle in the quantum state i at a point $\mathbf{r}$, which depends on the electric $\mathbf{E}(\mathbf{r})$ or magnetic $\mathbf{H}(\mathbf{r})$ field strength.

Magnetic interaction. For an atom or a molecule with a permanent magnetic moment $\boldsymbol{\mu}$ in an external magnetic field $\mathbf{H}$, the effective potential energy W is expressed as

$$W = -\boldsymbol{\mu}\mathbf{H} = -\mu_{\text{eff}} H , \quad (3)$$

where μ_{eff} is the projection of $\boldsymbol{\mu}$ in the $\mathbf{H}$ direction. The force F acting on the atom or molecule with a potential energy W is

$$\mathbf{F} = -\nabla W = -\frac{\partial W}{\partial H} \nabla H = \mu_{\text{eff}} \Delta H . \quad (4)$$

It follows from relations (2)–(4) that a particle in a nonuniform magnetic field experiences a force aligned with the field strength gradient.

The authors of Refs [25–28] proposed the idea of using a nonuniform magnetic field to focus the beams of molecules emitted from a source at different angles.

The focusing properties of magnetic lenses depend on the magnetic sublevels of an atom. This was used by Ramsey and his collaborators to make the hydrogen maser [29]. Hydrogen atoms residing in the state $F = 1$, $M = 0$ were focused on a small opening in the wall of a storage bottle and were accumulated in it, while the atoms in the ground state $F = 0$ were defocused.

Electric interaction. Because the energy of atoms or molecules in an electric field depends on the field strength, by analogy with expressions (3) and (4), an atom (a molecule) may be regarded as having the effective dipole moment

$$\mu_{\text{eff}} = -\frac{dW}{dE} . \quad (5)$$

The force acting on the atom (the molecule) in a nonuniform electric field is defined by an expression similar to (4):

$$\mathbf{F} = \mu_{\text{eff}} \nabla E = \mu_{\text{eff}} \frac{\partial E}{\partial z} , \quad (6)$$

where the direction of the field strength gradient is chosen to coincide with the z axis.

Paul and his collaborators [30] developed fields for focusing a beam of polar molecules. Townes, Basov, and Prokhorov resorted to the electric focusing of a beam of molecules residing in a specific (excited) state to make the NH_3 maser [31, 32].

Hexapolar electric fields have not only the focusing property but also selectivity relative to the quantum state of a molecule (μ_{eff} depends on the molecule quantum numbers J, K, and M). This property was validly used in experiments in molecular dynamics with the beam of molecules in a certain quantum state, including experiments on the orientation of molecules.

2.3 Laser fields

Atoms and molecules without a static magnetic or electric dipole moment cannot change their mechanical trajectory in a static magnetic or electric field. However, an atom embedded in a quasiresonance laser field has a high-frequency polarizability and, when the laser field strength is spatially nonuniform, the atom experiences a gradient (dipole) force [33]. For instance, the gradient force in a standing laser wave [34] may give rise to the channeling of atoms in their motion at small angles to the wavefront [35, 36] or even to their trapping by a three-dimensional standing light wave (which received the name 'optical lattice') [37, 38].

The gradient force was profitably used by Ashkin and his collaborators for focusing an atomic beam [39] and controlling the motion of microparticles [40].

Controlling atoms by light fields is underlain by the recoil effect. In the optical domain of the spectrum, the recoil effect experienced by an atom in the emission or absorption of light is quite small. High-intensity laser radiation tuned to resonance with some allowed dipole transition of the atom may give rise to the reemission of one million photons per second and may therefore have a significant effect on the velocity and trajectory of atomic motion. Hänsch and Schawlow [41] proposed the use of the resonance force arising from the spontaneous reradiation of photons, much like it was suggested for cooling ions in an electromagnetic trap [42].

Since that time, a new avenue in the development of atom physics has emerged reliant on the effects of resonance laser light–atom interaction with the use of the wealth of well-known effects of atomic physics: recoil, Doppler, Stark, Zeeman, and Raman scattering (RS) effects. This new avenue has led to the elaboration of highly efficient methods of laser cooling and the trapping of atoms (Fig. 1), which laid the groundwork for the formation of atom optics and the physics of degenerate quantum gases (BEC, Fermi-degenerate gases, etc.), as well for the making of the main tools of atom optics — atom lasers, atom interferometers, etc.

Gradient and spontaneous forces underlie numerous experiments in controlling atomic motion by means of light. Elements for which the laser cooling of atomic beams has been carried out are marked by circles in the periodic table shown in Fig. 2.

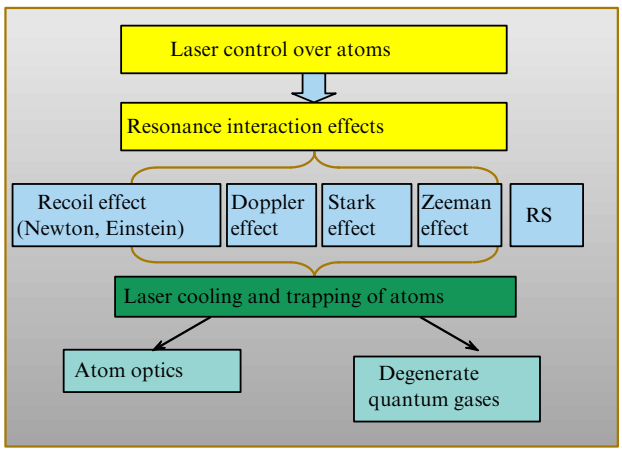

Figure 1. Diagrammatic illustration of the role played by the effects of atomic physics (recoil, Doppler, Stark, Zeeman, and Raman scattering effects) in the development of methods of laser cooling and trapping atoms and of atom optics.

3. Atom-optical nanotechnology

Atom optics holds good promise to make a contribution to nanotechnology, specifically to the investigation and fabrication of nanostructures. Neutral atoms, which are manipu-

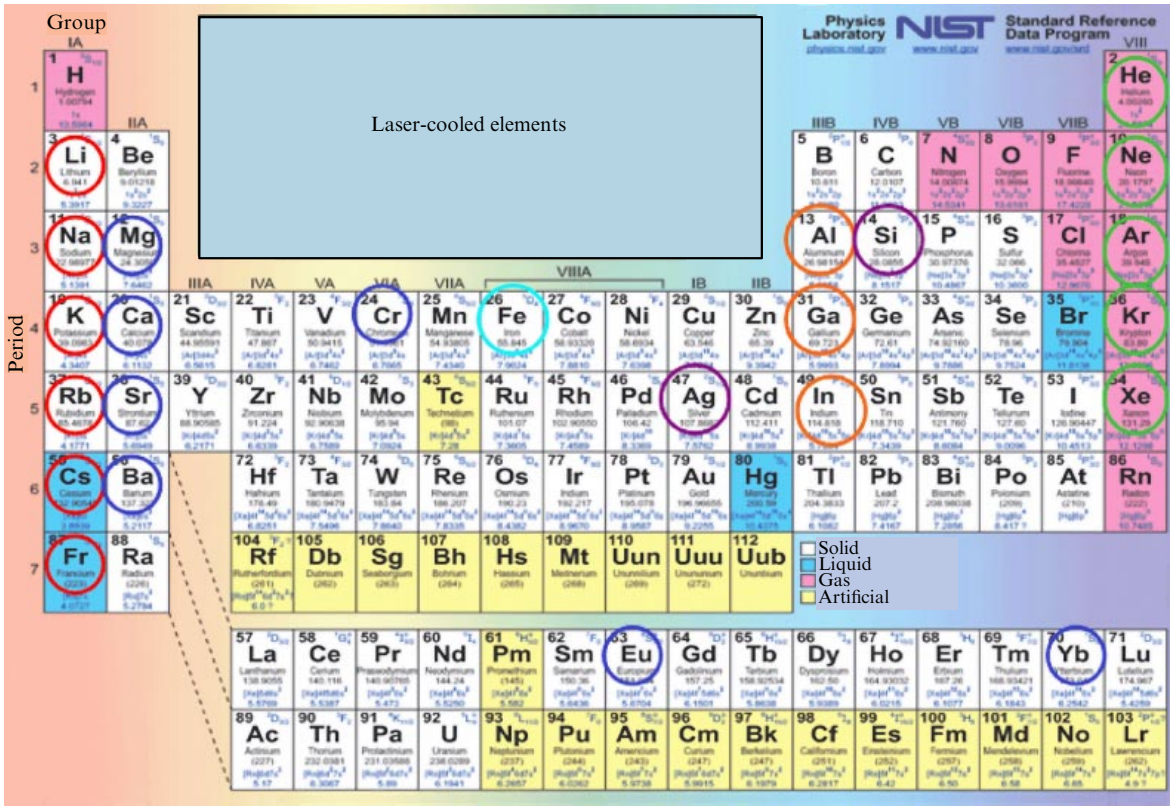

Figure 2. Elements (marked by circles) of the periodic table for which laser cooling of atomic beams has been carried out.

lated by means of different techniques of atom optics, offer certain advantages over other particles (ions or photons). First, neutral atoms have a short de Broglie wavelength λ_{dB} in comparison with photon wavelengths. Second, neutral atoms do not experience the Coulomb repulsion. Third, the methods of laser-assisted atom cooling enable controlling the longitudinal and transverse atomic velocities, collimating atomic beams, and increasing their phase density. (The latter signifies that the Helmholtz – Lagrange law and Liouville's theorem on the conservation of phase space volume, which substantially limits the capabilities of photon and ion optics, do not apply to atom optics.) All this permits controlling the parameters of atomic beams with the help of laser light, which is important in designing atomic and molecular nanostructures by the methods of atom optics.

The methods of atom optics are of special interest for nanolithography, which is referred to as atom-optical nanolithography. Nanolithography is quite often associated with the attainment of a high transistor number density on a chip, described by Moore's law (1965). Recent years have seen the successful advancement of optical lithography techniques using extreme vacuum ultraviolet (VUV) radiation and of lithographic techniques using electron and ion beams and X-ray radiation. These techniques permit producing nanostructures with a resolution of several nanometers. Meanwhile, extensive search for alternative lithographic techniques is underway. The following techniques are known today: (i) scanning nanoprobe, (ii) imprinting, and (iii) 'self-assembling' of nanostructures. The atom-optical methods discussed below should be considered from the standpoint of the search for the nanolithography techniques of the future.

Atom-optical lithography is represented by two main techniques: (i) direct deposition of atoms on a surface; (ii) lithography with the aid of excited (metastable) atoms and chemically active atoms (alkaline metals). Nanofabrication on a surface was realized in one-dimensional (1D) and two-dimensional (2D) versions in the form of regular and more complex structures. Demonstration experiments have been carried out for many atoms (metastable rare-gas atoms, nonmagnetic and magnetic atoms).

In what follows, we briefly consider the main achievements made in this area over the last 10 – 15 years, i.e., since the first successful experiments [43, 44]. This area in the development of nanotechnology is recognized to be quite promising, as is evidenced by the publication of numerous reviews [10, 45 – 49].

3.1 Direct deposition nanolithography

The direct deposition of laser-focused atomic beams was clearly demonstrated in experiments with a grid of 'photon lenses' in the form of standing waves [43 – 48, 50, 59]. This configuration of the light field permits obtaining a large number of periodically arranged nanostructures. Basically, many atoms having the corresponding quantum transitions may be used for atomic nanofabrication. The laser cooling of atoms may be effected due to cyclic quantum transitions, allowing the atoms to spontaneously reradiate the absorbed photons many times. Furthermore, the quantum transitions should have a wavelength at which available continuous-wave (CW) lasers operate.

A typical experimental layout suitable for many atoms is shown in Fig. 3. Even after passing through collimating apertures, the divergence of an atomic beam emerging from a thermal source is too high to attain a nanometer-scale resolution. In this case, the main feature of atom optics is first used: the capability of decreasing the transverse velocity

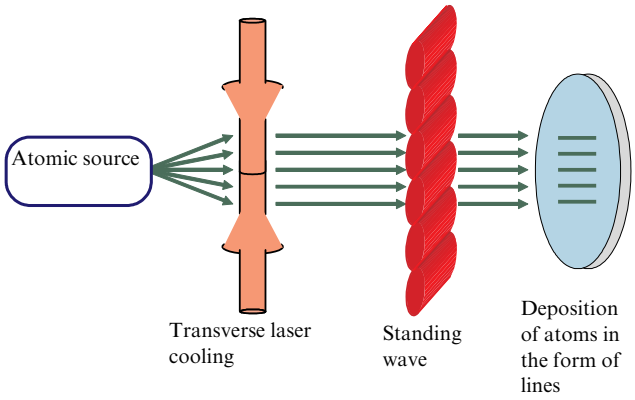

Figure 3. Direct-write nanolithography scheme. Two laser beams are used for the transverse cooling of an atomic beam. A standing light wave forms cylindrical photon lenses for focusing the atoms. The atoms are deposited on a surface to form parallel lines due to their focusing in the standing wave nodes, thereby forming a periodic nanostructure grating.

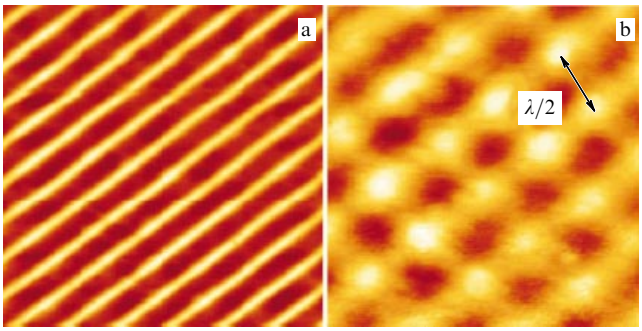

Figure 4. Images of chromium nanostructures fabricated by focusing with one-dimensional (a) and two-dimensional (b) photon lenses. The period of chromium lines and points is equal to $\lambda/2 - 213$ nm. The images were obtained with the aid of atomic force microscopy [52].

(temperature) of atoms by their transverse cooling (collimation), which was first demonstrated for an atomic sodium beam [51]. The barrier inherent in light optics due to the Helmholtz–Lagrange law is thus overcome in atom optics. The highly collimated atomic beam next passes through a high-intensity standing wave, whose frequency is shifted by several hundred MHz to the blue side of the spectrum relative to the atomic resonance frequency, with the result that the gradient force draws the atoms to the nodes of the standing wave, i.e. to the region where the potential energy of atoms in the light field is minimal. For atoms with a magnetic structure ($J \neq 0$), it is necessary to control the population of magnetic sublevels and afford the population of the state $|M| = J$ by optical pumping with circularly polarized light.

The first experiment following the scheme in Fig. 3 was performed with sodium atoms [43], which were deposited in the form of a grating of nanolines on a silicon substrate. The grating period was $\lambda/2 = 294.5$ nm, where λ is the wavelength of a dye laser tuned to the $3\,^2S_{1/2}$ $(F = 2)$–$3\,^3P_{3/2}$ $(F = 3)$ transition of the D_2 line (589 nm) of Na having the saturation intensity 6.3 mW cm^{-2} and the natural linewidth 10 MHz. The resultant gratings, which are unstable in the air, were studied in a vacuum also with the aid of light. The grating was initially recorded using the diffraction of shorter-wavelength laser radiation from this grating and then by scanning tunnel microscopy. The gratings of atomic Cs nanolines were produced similarly [50, 59].

It was not long before even more convincing experiments were performed Cr atoms [44, 52]. The advantage of using Cr atoms is that the Cr nanostructures fabricated in a vacuum survive in the air due to the formation of a very thin oxide film on them (about 1 nm in thickness). This permits investigating such nanostructures in the air with the help of an atomic force microscope. The experiments in Refs [44, 52], used transverse cooling of the atomic beam with the longitudinal temperature 1550–1650 °C by polarization gradient cooling [53, 54], which enabled obtaining a collimated beam with a divergence of only 0.1 mrad. Figure 4a shows images of chromium nanostructures in the form of lines. The halfwidth of the chromium nanolines was equal to 50 nm, and the height (22 nm in Fig. 4a) depended on the exposure time (several tens of minutes). The resultant background is, in particular, due to Cr isotopes that were out of resonance with the laser radiation. By using two mutually orthogonal standing waves, it was possible to fabricate a 2D grating of 'photon microlenses' and fabricate a two-dimensional nanostructure on the surface (Fig. 4b) [52, 55]. The same technique was used to obtain nanostructures with the minimal dimension of only 15 nm [56].

These pioneering experiments provided the foundation for subsequent experiments with other light field configurations, atoms, and substrates.

A standing light wave is perfectly suited for fabricating 1D periodic structures (line gratings) and 2D periodic structures (gratings of points). By varying the wavelength, it is possible to control the grating period ($\lambda/2$). By varying the polarization in the standing wave (for instance, by using two counterpropagating waves with orthogonal linear polarizations), it is possible to obtain the period $\lambda/8$ [54]. Owing to the complex interaction of all magnetic sublevels of ground-state Cr atoms with the light polarized this way, the optical potential varies in space with the period $\lambda/8 = 53.2$ nm. However, this simultaneously decreases the modulation depth of the resultant array of atomic nanolines.

The interference of three laser beams intersecting at an angle of 120° can also be used. In this case, the two-dimensional picture has a hexagonal symmetry, which may be additionally controlled by varying the detuning Δ of the field frequency relative to the atomic resonance frequency, drawing atoms to either the nodes ($\Delta > 0$) or the antinodes ($\Delta < 0$) of the interference pattern [57]. In another experiment, a decagonal quasiperiodic structure of ^{52}Cr atoms with the surface area 0.2×0.2 mm was fabricated with the aid of five laser beams intersecting at 72° [58].

The complexity of structures depends on the configuration of the light field produced by the superposition of many laser beams. Complex configurations may be obtained by holographic reconstruction of the light field [59]. The use of holographic techniques holds much promise due to the high angular and spectral selectivity of the holographic 'mirror.' In particular, one hologram may retain holographic images for two different wavelengths, which conceptually permits producing the field for two different atoms in one experimental setup with different configurations of the light field.

Also important for practical purposes is the fabrication of 3D structures. So far, this field has not been adequately developed. However, 3D structure formation has been successfully demonstrated using a combination of Cr atoms and MgF_2 material [52]. In the experiment reported in Ref. [52], the atoms of ^{52}Cr experienced resonance interac-

tion with a standing light wave, which permitted a laterally modulated density of MgF_2 doped with Cr atoms, while MgF_2 was deposited without experiencing an appreciable influence from laser radiation (large detuning of the laser frequency). It is believed that using combinations of atoms of groups III and IV with laser fields at the corresponding two resonance frequencies will allow fabricating laterally modulated heterostructures, which is of interest in constructing metamaterials.

A beam of magnetic Fe atoms became the next experimental subject, and a more difficult one at that [60, 61]. Shorter wavelength radiation ($\lambda = 372$ nm) is required to effect resonance excitation in this case. Furthermore, laser cooling is more difficult to realize because the Fe atom does not have a perfectly closed cyclic transition. An excited Fe atom returns to a metastable state instead of the initial state with the probability 1/243 and moves out of resonance with the radiation. Nevertheless, it was possible to fabricate the gratings of 50-nm-wide nanolines with the regular period 186 nm [62] in these experiments. Such highly regular ferromagnetic nanogratings may be used in experiments in spintronics and with nanomagnets. The use of shorter wavelength lasers will enable the pursuance of nanofabrication experiments with other magnetic atoms, ^{58}Ni (323.4 nm) and ^{59}Co (240.5 nm).

Successful experiments were carried out with atoms of rare-earth element Yb [63]. The prospects of experiments with the potentially important atoms ^{27}Al (309.4 nm), ^{69}Ga (294.4 nm), and ^{115,113}In (325.7 nm), which necessitate CW lasers in the poorly mastered UV range, were considered in [64].

For nanofabrication purposes, only several simple configurations, such as a standing light wave, and their combinations have been used so far, and hence there is much room for future research.

3.2 Nanolithography of a resist

Conventional lithographic techniques involve a resist (a thin film on a substrate), in particular, a photoresist sensitive to UV or VUV radiation. The same method may be used for nanolithography with a light mask (see Fig. 3). The light mask produces a spatially nonuniform distribution of excited (metastable) or chemically active atoms, which modify the resist. The subsequent etching of the exposed resist is performed by standard lithographic techniques. Suited for this approach to nanofabrication are substrates of any material that lend themselves to etching, including important magnetic materials like Ni and Fe. Nanofabrication techniques involving excited (metastable) rare-gas atoms (He*, Ne*, Ar*) and chemically active atoms of alkaline metals (Na, Cs) were demonstrated.

Metastable rare-gas atoms. The first resist used in nanolithography was a self-organizing monolayer (1.5 nm thick) of dodecanthiol on a gold-coated substrate [54]. The molecules of the highly ordered monolayer make up a hydrophobic surface, which protects the substrate from chemical etching in an aqueous solution. Metastable atoms with a high internal energy (up to 20 eV for He*) or chemically active atoms disrupt the local ordering of the organic molecules, making subsequent local etching possible. This technique, which relies on a light atom-excitation mask, was demonstrated for a standing light wave [55]. Nanostructures of the size 65 nm determined by the wave nature of atoms were obtained in experiments [65].

Instead of the local disruption of a self-organizing molecular resist film, the disruption in the film of background oil molecules deposited on the resist surface by an oil pump in the course of experiments can be used. The spatial structure of local disruption in this background film may be transferred onto the substrate for subsequent etching by the ion beam [64, 66].

Chemically active atoms of alkaline elements. Such atoms can be focused by means of the gradient force of the light field of both continuous and pulsed lasers; due to their high chemical activity, these atoms can modify surfaces on a nanometer scale.

3.3 Atomic nanopen lithography

The transportation of atoms through a hollow fiber waveguide [67] and their focusing in the near field of a nanoaperture [68] are the heart of the idea of an atom-optical 'pen,' which is schematically shown in Fig. 5. A hollow fiber or a screen with a nanoaperture may be translated laterally with a cantilever, which has been validly used for nanofabrication by the direct deposition technique [69]. The laser cooling, collimation, and focusing of an atomic beam may be effected in a tapering (bugle-like) hollow optical waveguide [70]. The use of an atom pen may become a universal way of 'nanowriting' [48, 71], although there are evident limitations on the productivity of this process due to the slow scanning procedure.

Conceptually, nanowriting may also be effected by a spatial scan of the de Broglie atomic wave by laser light. Such an atomic scanner has already been demonstrated in experiment [72].

3.4 Atom pinhole camera

An experimental approach to atom optics based on the idea of constructing images of an object with the aid of a pinhole camera, which is well known in light optics, was first

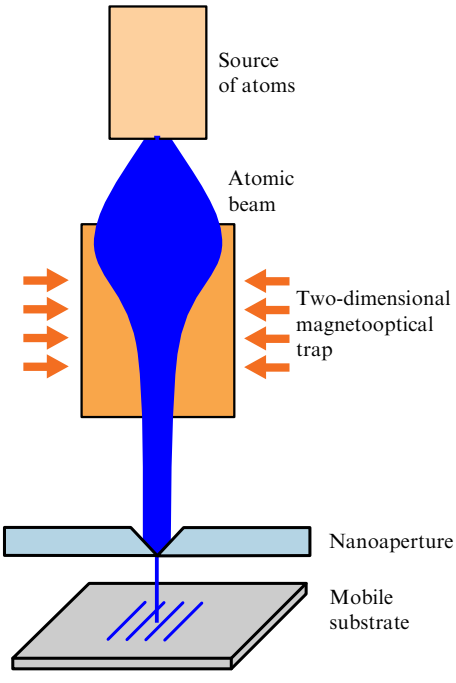

Figure 5. Schematic of an atom-optical pen for 'nanowriting' atomic structures [48, 71].

experimentally realized in Ref. [71]. Pinhole cameras are also used in modern experimental physics when the focusing potential is difficult to organize [73, 74].

A consideration of the optics of an atom pinhole camera shows [71, 75] that the realization of such a camera requires a screen of nanometer thickness with an opening a nanometer in diameter. The layout (Fig. 6a) of the atom pinhole camera comprises an atomic beam, a mask, an opening a nanometer in diameter, and a substrate on which nanostructures are fabricated. The atoms transmitted through the opening in the mask, as in optics, form 'a luminous object' with the desired geometry. The parameters of the atom pinhole camera are selected in such a way as to maximize the camera resolution and to fabricate as large a nanostructure array on the surface as possible, which is achieved by using an array of nanoopenings. It has been shown that the optimal focal distance is $f_{\rm opt} \approx 10-20$ μm when thermal atomic beams with typical de Broglie wavelengths of the order of 10^{-3} nm and an opening 20 nm in diameter are used. These considerations determine the choice of the distance l between the nanoopening and the substrate: $l = f_{\rm opt}$. For a given distance l, the nanoopening–mask distance determines the 'demagnification' of the object of the atom pinhole camera and hence the size of the mask itself.

The above considerations show that the optimal nanoopening–mask distance is in the range $L = 1-10$ cm. In this case, the 'demagnification power' $N = L/l$ of the atom pinhole camera is equal to 10^3-10^4. In this geometry of the atom pinhole camera, the characteristic mask dimensions are in the micrometer range and the characteristic dimensions of the structures fabricated on the surface are in the nanometer range; hence, the atom pinhole camera affords transformation of microworld objects to objects of the nanoworld. Another important implication of the 'dimension geometry' of the atom pinhole camera is the opportunity of using not one nanoopening but a large array of nanoopenings in one device. In this case, each nanoopening produces an image of its own, which does not overlap with the neighboring ones, and it is therefore possible to realize a multiple atom pinhole camera. Such an atom pinhole camera opens up the door to simultaneous fabrication of a large number of identical nanostructures. We note that the aberration of inclined beams does not appreciably limit the resolution of a multiple atom pinhole camera even for a large number of nanoopenings (up to 10^6).

An atom pinhole camera was realized in the geometry considered above and was used to fabricate nanostructures of different metal atoms on the surface of an insulator.

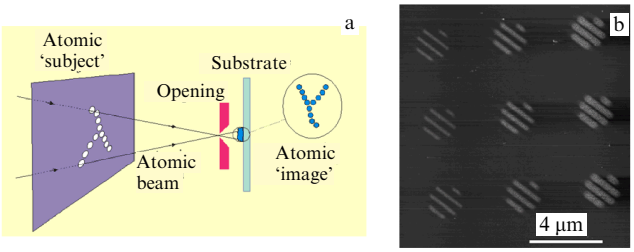

Figure 6. (a) Schematic representation of an atom pinhole camera. (b) Image of In atomic nanostructures on a silicon substrate. The mask was a metal screen with a grating of a series of strips of different widths: 40, 100, and 250 μm. The nanostructures reproduce the mask geometry with a specified demagnification coefficient equal to 3000 [75].

Figure 6b shows the image of the nanostructure of In atoms obtained with an atomic force microscope (from the Veeco Company). The mask was a metal screen with a grating of a series of strips of different widths (40, 100, and 250 μm) made by laser cutting. The distance between the strips in the mask was 1 mm. The nanoopening diameter was $s = 200$ nm. The nanostructures shown in Fig. 6b reproduce the mask geometry with a specified demagnification coefficient equal to 3000. It can be seen from the figure that the strips forming the nanostructure are different in height, because each of the strips is made up of atoms transmitted through mask slits of different widths. This circumstance may be of significance in the fabrication of nanostructures with a complex three-dimensional geometry. The shape of nanostructures is determined by the arrangement of openings in the mask, while the heights of individual nanostructure elements are determined by the diameters of the corresponding openings.

To find the ultimate parameters of the atom pinhole camera, measurements were made in the experiment in Ref. [75] on nanostructure fabrication through varying the nanoopening diameters over a wide range: from 250 to 20 nm. This allowed operating the atom pinhole camera both in the mode of geometrical optics and in the mode of wave optics. In the latter case, the effect of atom diffraction through nanoopenings becomes significant.

4. Summary

We have discussed approaches to nanotechnology based on atom optics techniques. In atom optics, the internal and external degrees of freedom of individual atoms are controlled by laser fields with nanometer accuracy, which allows fabricating structures with nanometer accuracy on a surface.

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Spectroscopy of ionized atoms for astrophysics and nanotechnology

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1. Introduction

Spectroscopy of ionized atoms is an important tool in the solution of scientific and technological problems in different fields of physics. The results of investigations of ion spectra were and are used in solar and stellar research, for the diagnostics of laboratory plasma sources, including the controlled thermonuclear fusion problem, and for high-resolution optical microscopy and lithography. The Department of Atomic Spectroscopy of the Institute of Spectroscopy, RAS (ISAN) has been pursuing research in the majority of these areas since the inception of the institute. The Department now has a unique experimental, theoretical, and methodological basis sufficient for analyzing the most complex ion spectra and validly applying the data acquired. In this report, we consider two relatively distant areas of application of the spectroscopy of ionized atoms: investigations into the atmospheres of peculiar magnetic stars and the development of efficient optical lithography sources in the far vacuum ultraviolet (VUV) domain.

A group of stars relatively close in properties, whose spectra exhibit high-intensity absorption lines of heavy elements, which are quite weak or not recorded at all in the spectra of the main-sequence stars, have long been the particular concern of astrophysicists. Absorption lines of rare-earth ions, and sometimes of heavier elements up to Pt, Bi, and U, are recorded in the stellar atmospheres of this group. The masses of these stars range from 2 to 5 solar masses, their surface temperatures lie between 7000 – 18000 K, and most of them have high magnetic fields up to 10 – 30 kGs, strong atmospheric turbulence, and pulsating intensities in their absorption spectra. These objects are known as peculiar magnetic stars and are often referred to as Ap stars in the literature. The atoms of rare-earth elements in the atmospheres of these stars are primarily in the first and second ionization stages, whose spectra have not been adequately studied [1 – 3]. In many spectra, especially in the spectra of doubly ionized atoms, only several tens (out of several thousand possible) lines lying in the visible range (transitions between low levels) have been identified. The transition probabilities (line strengths) calculated for doubly ionized rare-earth atoms and stored in DREAM (Database on Rare Earths at Mons University) [3] are restricted to the transition probabilities between a small number of the known energy levels. Determining the composition and parameters of the atmospheres of Ap stars, defining relevant processes more precisely, and accounting for the emergence of their special features requires data, as comprehensive as possible, about the corresponding ion spectra, which are practically the only source of information about these objects. In Section 2, we