Atom optics as alternative tool to plasmonic metamaterials

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Abstract

We review current status and perspectives of atom optics approaches for creation and characterization of plasmonic nanostructures manufactured on a substrate. Advantages and limitations of nanolithography based on atom optics methods and its application in production of nanostructures with plasmonic properties is considered.

1. Introduction

Atomic and molecular nanostructures on a surface of a solid are key components in modern technologies. As it was recently demonstrated, by proper arrangement of nanostructures of a special geometry on a substrate, materials with unique optical properties can be created – photonic metamaterials. Nanostructures creation and arrangement on a substrate is one of the key problems in fabrication of such materials. In practice it is desirable to have the ability to build 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. At present, the most developed methods for surface nanostructure creation are optical photolithography and nanolithography based on use of charged particles (electrons and ions). An alternative for nanotechnology is *atom optics* [1].

Atom optics formed into a separate physical discipline in the mid - 1980s as a result of investigating the influence of the forces of laser light pressure on the “atoms’ motion”. Atom optics, similar to electron, ion, and neutron optics, is related to particle optics and considers the problems of the formation and control of ensembles and beams of neutral atoms and their application. The development of atom optics is closely connected with the development of methods of laser cooling and localization of neutral atoms. The laser cooling of atoms and their spatial localization form atomic ensembles and beams with given parameters. Laser cooling provides a decrease in the atomic temperature to about several μK. At such temperatures the De Broglie wavelength becomes comparable to the light wavelength and the wave properties of atoms begin to manifest. The localization of neutral atoms opens up the possibilities of operating with both single atoms localized with a nanometer precision [2] and macroscopic ensembles of cold atoms with high phase density. Based on different configurations of laser light fields and mechanical micro and nanostructures (zone plates, multislit diaphragms, etc.), many atom optics elements have been created: lenses, mirrors; coherent atomic beam splitters; atomic interferometers; waveguides; and finally, an atom laser, which is an analogue to the optical laser. It should be stressed that the capabilities of atom optics are much broader than other types of particle (electron and neutron) optics due to the internal structure of the atom.

Among many direction of research in atom optics a potentially important one is micro- and nanofabrication of material structures, usually referred to as atom lithography [3]. In this method, internal and external atomic degrees of freedom are controlled to a very high precision by external electromagnetic fields (or material structures) and thus results in high-resolution surface patterning [4,5].

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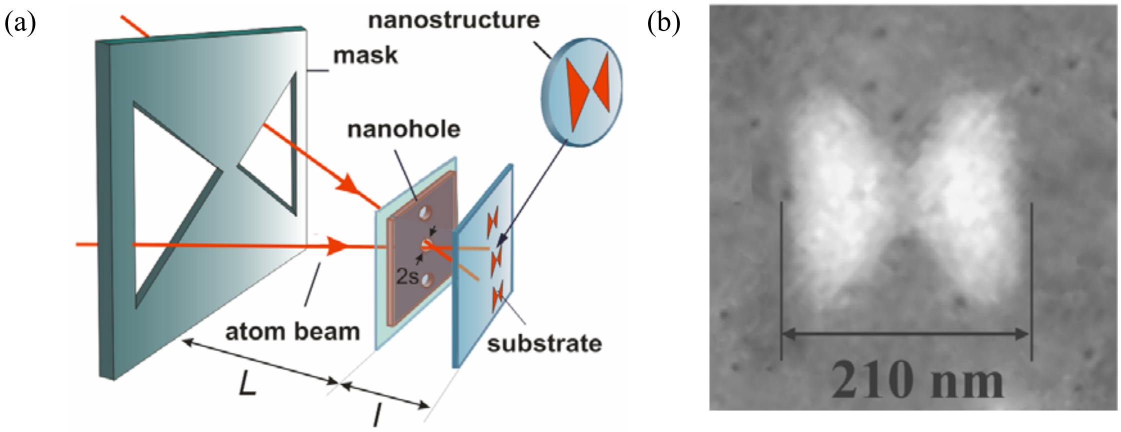

Fig. 1: (a) Schematic diagram of an atom pinhole camera. An atom nanostructure whose shape is a reduced copy of the mask is created on the substrate using the nanohole. (b) AFM image of nanostructure formed by Au atoms on a glass surface in a shape of a “bow - tie” nano antenna. The nanostructure was produced by nanolithography based on an atom pinhole camera.

2. Nanolithography with atom optics

In spite of the presence of multiple proposals for focusing atomic beams and multiple experimental atom lenses being achieved, the problem regarding the construction of nanoobjects of an arbitrary shape has not yet been solved. The main complexity is the creation of atom–electromagnetic field interaction potential with properties close to those of the “ideal” lens for atoms (with minimal chromatic aberration and compensated astigmatism, which provides atomic beam focusing into a diffractionally limited spot).

In [6] a new approach to constructing object images in atom optics based on the idea of the pinhole camera, which is well known in light optics, was first experimentally achieved.

The schematic diagram of the pinhole camera achieved in experiment is shown in Fig. 1(a). It includes the atomic beam, the mask, the membrane with nanoholes, and the substrate on which nanostructures were created. Atoms that passed through the hole in the mask form, similarly to optics, the “glowing object” with the given geometry. The parameters of the pinhole camera is chosen from the considerations of obtaining maximal resolution and the possibility of constructing of a large array of nanostructures on the surface. If thermal atomic beams with typical de Broglie wavelengths of around 10–2 nm and a nanohole with a diameter of 20 nm are used, the optimal focal distance is *f*opt ≈ 10–20 µm. This determined the choice of the distance between the nanohole and the substrate on which nanostructures were created ($l = f_{opt}$). Fig. 1(b) presents example of nanostructure created with use of atom pinhole camera nanolithography. Nanolithography based on atom pinhole camera was used to create nanostructures from In, Cr, Au and Ag atoms on a silicon and glass surfaces [6-9].

3. Creation and characterization of plasmonic nanostructures

Nanolithography with atom optics opens up wide opportunities for simultaneous generation of great numbers of nanostructures for fabrication of metamaterials: (1) with nanostructures’ position and size disorder [6], (2) lithography of identical nanostructures arranged on to the substrate surface in the appropriate ordered way [8].

Our resent research show advantages of use atom optics approaches in applications for production of nanophotonics and nanoplasmonics elements: optical Au nano antennas (in a bow tie and nanorods geometry), Au plasmonic wave guides, nanostructures formed by tris (8-hydroxyquinoline) aluminum (Alq3) (organic molecules typically used for OLED applications). Comparison of theory with experimental data of absorption spectra (Fig. 1) and local field enhancement factor for created nanostructures shows dominant role of localized plasmon oscillations.

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In a separate research role of surface plasmons in the effect of extraordinary optical transmission through nanoapertures of different configurations was studied. It was shown that use of atom optics methods to control creation of open apertures in thin films is essential for number of applications.

(a) (b)

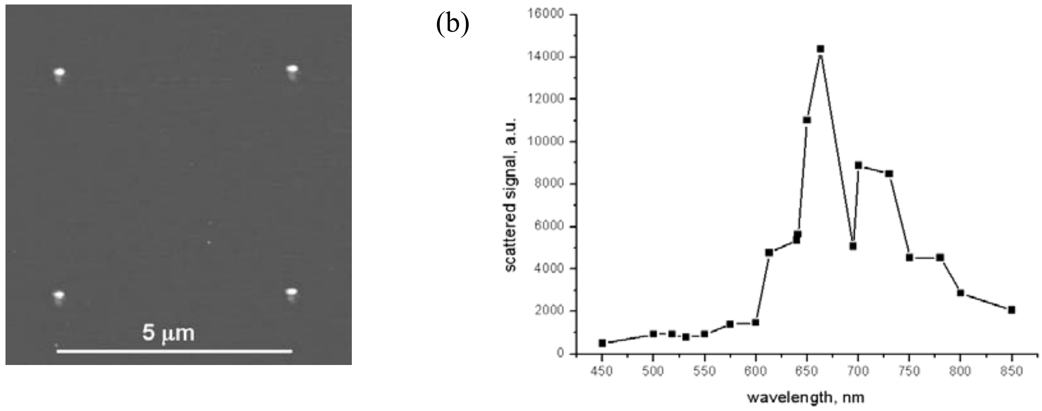

Fig. 2: (a) AFM image of four Au nanostructures in a shape of nanorod arranged on a glass surface; (b) Absorption spectra of individual nanostructure presented on a Fig. 1(a).

4. Conclusion

Nowadays, important fundamental studies in the field of manipulation with free neutral atoms using the methods of atom optics have been performed and methods for constructing basic optical elements on matter structures, static electric and magnetic fields, and laser fields have been developed. Based on these methods, approaches providing the high-precision control of the motion of atoms as they approach the surface have been developed; this resulted in the development of one practically important direction for atom optics: atom nanolithography.

Our research show that nanolithography based on atom optics methods has a number of benefits for creation of plasmonic nanostructures: (1) it makes possible nanostructures with typical size down to 20 nm; (2) the nanostructures can have an arbitrary prearranged shape; (3) size and form of nanostructures are governed by well controlled parameters; (4) creation of a great number of identical nanostructures is possible; (5) a variety of materials for nanostructures (atoms, molecules, clusters) is feasible; (6) the methods are free from use of a chemically selective etching; (7) in the process of nanostructures creation no destruction of the substrate surface happens.

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