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Optical shaping of surface metal microstructures via nondiffracting beam controlled atomic deposition

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ABSTRACT

The first experimental realization of the non-diffracting Bessel beam technique for micro-structuring of thin rubidium metallic films on the sapphire surface is reported. Rubidium atoms were deposited onto the cool sapphire windows from the heated central region of the evacuated cell under simultaneous illumination by a Bessel beam at 532 nm wavelength and 4.5 W/cm^2 intensity. The approach of the optically controlled atomic deposition is based on the strong non-thermal photo-desorption of atoms from illuminated areas of dielectric surface diminishing the surface density of adsorbed atoms below the threshold of nucleation process, while in the dark areas concentration of adsorbed atoms exceeds the critical value and a metal film starts to grow. As a result, the annular Bessel beam optical pattern with 40 μm periodicity was reproduced with high contrast in the Rb deposits, thus creating the annularly micro-structured metal film on the sapphire surface. The diffraction efficiency of the metal grating with the estimated thickness of ∼40 nm was measured to be about 1.8%.

1. Introduction

Planar micro- and nanophotonic devices are the subjects of an increasingly developing area of research because of the wide spectrum of applications in optoelectronics and photonics, which include the domains of display devices, sensors, optical communication systems, nano-photonic devices, metamaterials etc [1–4].

Among different technologies to manufacture the metallic, semiconductor or organic nanostructures the molecular beam epitaxy, mask and interference photolithography, as well as electron beam lithography are leading [1,4]. Electron beam lithography (EBL) remains the most powerful method for generation of lithographic patterns in the mentioned domains due to the combination of high precision, better than 50 nm, and programmability. In spite of many advantages the EBL technique is multi-step and requires very expensive equipment and long processing time.

In this respect the *bottom-up* technologies based on the self-organized and photoinduced formation of nanostructures [5,6] are favorable alternatives. These technologies are single-step. However, the resulting nanostructures topology is rather irregular.

An attractive possibility to produce metal micro- and nanostructures is the light induced atomic desorption as a tool for controlling the surface atom density of the adsorbed atoms (adatoms) in the course of the physical vapor deposition process [7].

The non-thermal light induced atomic desorption of the alkali atoms Na, K, Rb, Cs from surfaces of sapphire [8–10], porous glass [11–14], as well as organic compounds, namely, polydimethylsiloxane [15,16] and paraffin [17], have been studied. Adsorption-desorption experiments were performed for Zn and Sn in [18]. Special attention was devoted to noble metals, gold and silver, adsorbed on different materials. The deposition of the silver on the silver chloride single crystal and silver adatoms optical absorption spectra have been studied in [19]. An analogous experiment with the gold atoms deposited on amorphous silica was performed in [20].

Optical shaping of the metal microstructures can be performed by *nonuniform* illumination of the substrate in the course of physical vapor deposition process. Our approach is based on the following processes. The strong enough nonuniform illumination diminishes the surface density of the adsorbed atoms in illuminated areas below the threshold value necessary for beginning of the nucleation process. At the same time in the dark areas the concentration of adsorbed atoms exceeds the critical value and a metal film starts to grow. As a result, the deposition pattern will reproduce the spatial distribution of the illumination intensity over the surface.

The nonuniform light beam can be obtained by mask or interference techniques. In [10] the nonuniform light beam was obtained by illumination of the substrate through the copper wire grid with a pitch of 100 μm and in [21] with the use of the optical test pattern (mira)

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providing 10 µm periodicity. In [22] for creation of a micrometric scale metallic grating the spatial profile of the resonant laser beam was modulated with the reflection from a Fresnel mirror. The feasibility of the interference technique to produce surface structures with a pitch of 260 nm was substantiated in [9].

For laser methods the achievable pattern density is restricted by the applied optics aperture and by beam diffraction, thus limiting the fabrication of high contrast and sub-wavelength size textures. From this point of view, the non-diffracting beams give an advantage for providing high contrast of the metallic micro-structured pattern. The suggestion to use nondiffracting optical beams for high contrast microstructuring of surface metal films was done in [21]. Exposing the atomic deposits on the substrate surface with the periodically or quasiperiodically spatially modulated non-diffracting beams has an advantage since the light intensity distribution is stable in the course of beam propagation, providing high contrast of the metallic micro-structured patterns.

The specific feature of the adsorbed atoms is wide absorption and desorption spectra [8,23] with maxima located near the wavelengths of the resonance transitions in the corresponding free atoms. For example, the optical spectrum of rubidium loaded porous glass was studied in [11–13] and showed a wide band stretching from 500 nm to 1100 nm with the maximum near 850 nm. Wide absorption and desorption spectra of adatoms provides flexibility for choosing the wavelength of the laser source to initiate the photodesorption process.

The deposition of sodium atoms on the sapphire substrate optically controlled by the Bessel beam at 532 nm wavelength leading to the formation of a micrometric scale annular metal grating was demonstrated in [24]. To prove the general nature of the suggested approach for microstructuring of thin metal films and advantage of optical control by nondiffracting beams it was reasonable to realize the method for other alkali atom such as Rb.

In this paper we report the first experimental realization of the non-diffracting Bessel beam technique for micro-structuring of thin rubidium metallic films on the surface of sapphire. We used a cell with a side arm, which allowed us to demonstrate the novel feature of simultaneous optical shaping of metallic structures on both input and output windows of the cell with high contrast. The high contrast of the fabricated annular metallic grating allowed the observation of the probe beam diffraction on the grating and of the diffraction efficiency measurement of thin metallic grating.

2. Experimental arrangement

The experimental arrangement is shown in Fig. 1. The experiments were performed in a cylindrical pyrex cell with sapphire windows and with a side arm functioning as a Rb reservoir. The length of the cell was 26 mm and diameter of sapphire windows was 15 mm. The cell was previously evacuated, filled with rubidium and sealed off. The metal

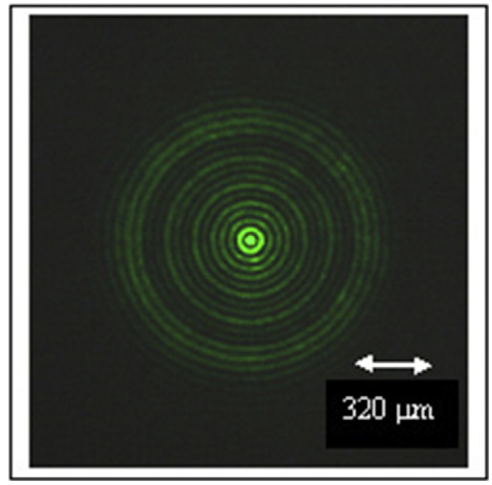

Fig. 2. Bessel beam transverse profile with 40 µm periodicity.

drop was placed in the side arm which was heated to the temperature of 120 °C, corresponding to the atomic density of 10^{13} cm^{-3}. The windows of the cell were kept at room temperature.

The optical part of the setup consists of a Gaussian beam, derived from a cw single mode 532 nm laser with the maximum power of 140 mW. The non-diffracting zero-order Bessel beam was used in the experiment [25]. The profile of the Bessel beam is a set of concentric rings [26]. The optical element axicon [27] was used in the experiments for formation of the Bessel beam.

The laser beam was expanded by an optical 20× telescopic system and after passing through an axicon with the apex angle of 178° (Altechna APX-2-VIS-H254,) was transformed to the Bessel beam. The distance along the Z axis where the converging beams are overlapped and form the Bessel beam (Fig. 1) was measured to be Z_{max} ~ 100 cm. The spacing between the concentric rings was measured by the beam profiler Thorlabs BP109-VIS and equaled to 40 µm. The beam profile consisting of concentric rings with radial periodicity of 40 µm is shown in Fig. 2.

The Rb cell was placed in the Bessel beam zone in such a way that the input and output windows of the cell were near the center of the Bessel zone. The Bessel beam intensity on the cell windows was estimated to be ~4.5 W/cm^2. The deposition process runs under continuous illumination during 30–60 min. This provides the non-uniform spatial distribution of the illumination intensity over the sapphire windows and the optical control of Rb atoms deposition and formation of annular metal micro-structures induced by the Bessel beam. After the end of the laser-controlled deposition process the obtained rubidium deposits on the cell windows were examined by the reflective optical microscope.

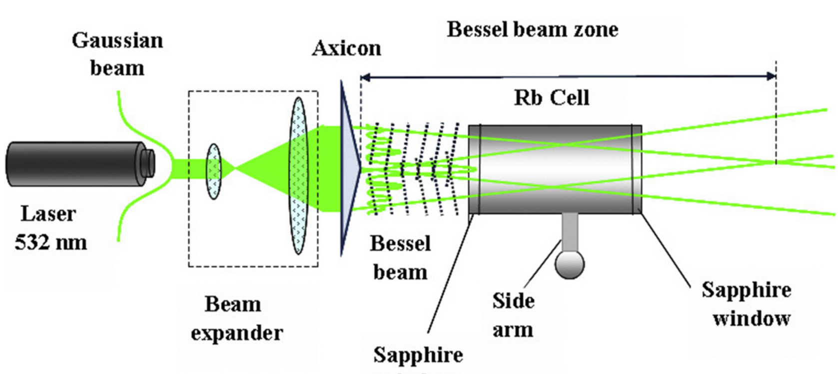

Fig. 1. Experimental setup. The size of the cell (2.6 cm) is shown enlarged relative to the Bessel beam formation zone of 100 cm.