Optimization of the photonic crystal colloidal films deposition by means of atomic force microscopy

E V Panfilova¹, A B Syritskii² and A R Ibragimov¹

¹Department of Electronic Technologies in Mechanical Engineering, Bauman Moscow State Technical University, 105005 Moscow, Russia
²Department of Metrology and Interchangeability, Bauman Moscow State Technical University, 105005 Moscow, Russia

panfilova.e.v@bmstu.ru

Abstract. This article describes the results of optimization of the colloidal photonic crystal opal films deposition by means of atomic force microscopy investigation. The main factors affecting the quality of the colloidal opal films are studied. Bragg diffraction occurs in the periodic distribution of colloidal microspherical particles, and ordered structure is critical for formation of the photonic band gap. It is found that polystyrene opal structures obtained in optimal conditions have a good periodicity, uniformity, and high packing density.

1. Introduction

Today it is already well known that the physical properties of nanoparticles and clusters, determined by their extremely high specific surface area, can differ significantly from the microscopic characteristics [1]. The ability to study nanostructures with high spatial resolution quickly and efficiently is an important question in the development of nanotechnologies. The atomic force microscopy (AFM) has been demonstrated to be capable to investigate almost any kind of samples without any sample preparation with nanometre resolution. This method is widely used in nanostructures research [2]. One of the perspective nanostructured materials is an artificial opal [3,4]. Because of high periodic regular structure, opal films can block the light spreading in wavelength range forbidden for this structure. Colloidal films with the structure of opal matrix can be used in photonics, optoelectronics, sensors, micro- and nanoelectronics, and other various devices and technologies [5,6]. While various strategies have been developed to direct the self-assembly of colloidal particles, fabrication of crack-free and transferrable colloidal film with controllable crystal structures still remains a major challenge [7]. This article describes the polystyrene opal film deposition process and its optimization procedure that was implemented using operating AFM control.

2. Experimental

The original method of vertical lifting was used as the opal film deposition method [6]. The substrate is placed vertically in a colloidal suspension of microspheres and is gradually exposed by evaporation or other slow solvent removal at a rate in the range from 0.1 to 10.0 mm/min [8-10]. While lifting, the capillary forces attract the microspheres nearest to the substrate to their surface. It makes possible to obtain sufficiently large-area colloidal opal films by vertical deposition method and to parametrize the deposition conditions for optimal film growth. Figure 1 shows the general scheme of the vertical deposition method.
Figure 1. The schematic diagram of the vertical deposition method.

The structure of the obtained films was monitored by measuring the relative area of ordered structure by means Solver Next scanning probe microscope (NT-MDT, Russia) in the atomic force semi-contact mode [11]. The photonic properties of the obtained opal matrices were monitored by measuring the reflection coefficient of the photonic band gap (PBG) using Epsilon spectrophotometer (IZOVAC, Belarus).

3. Results and discussion
Colloidal polystyrene monodisperse latex was used as a material for the formation of opal matrix. A preliminary experiment was performed using 10% colloidal solution with particles diameter 220 nm at lifting velocities of 1 and 0.8 mm/min. Films were deposited on the sitall CT-50-1 substrates with a working surface roughness of less than 0.032 μm.

Analysis of macroscopic images and topological analysis of the first obtained samples showed that the films did not have the required uniformity parameters. In this case, the photonic properties of the obtained structures were weakly expressed. Figure 2 presents the results of studies of obtained polystyrene films.

Figure 2. (a) AFM image and (b) the reflection spectrum of the polystyrene film obtained during the preliminary experiment at the 1 mm/min lifting speed.
The process of obtaining colloidal films was optimized by the results of the full factorial experiment. Fifteen observations were carried out for every coordinate plane point. The lifting velocity was varied from 0.1 to 0.5 mm/min, the solution concentration – from 1 to 5%, and particles diameter – from 220 to 330 nm. The relative area of a structurally ordered film and the reflection intensity of the PBG were controlled. Regression equations were considered as joint estimates of linear effects and interaction effects [12]. The results of the full factorial experiment revealed areas of factor space, in which the films were well deposited and opal matrix had a good periodicity, uniformity, and high packing density. To optimize the process, the gradient method was used. Figure 3 shows optimization schemes for 220 nm particles film.

The optimization results revealed that for particles diameters varying from 220 to 330 nm lifting velocity of 0.3 mm/min and solution concentration of 5% make it possible to obtain the most uniform opal colloidal films with pronounced photonic crystal properties. The deposition process allows the opal films to have periodical structure and uniformity. Every particle connects with its neighbours without any defects. As a consequence of its structure periodicity, all obtained films show opalescence: reflected colours that come from the Bragg diffractions in the periodic distribution of microspheres. The greatest reflectance was 24%. The reflection spectrum and the surface structure for 220 nm particles film are shown in Figure 4.
Concentration of more than 10% leads to agglomeration of the particles and appearance of large clusters of particles on the substrate. At velocities more than 1.5 mm/min, no deposition or empty plots of substrate were seen.

4. Conclusion
The vertical deposition process was optimized to allow depositing qualitative opal film. Operational quality control of the films was carried out using AFM. We have fabricated polystyrene opal matrix of particles with diameters ranging from 220 to 330 nm and less than 2% dispersion of Bragg stop band position. The results of the reflectance measurements and AFM investigation of deposited film show that polystyrene particles have been obtained using 5% colloidal solution and the vertical lifting velocity of 0.3 mm/min. The authors see the development of the work in the research of the phenomenon of self-assembly.

References
[1] Garishin O and Lebedev S 2013 PNRPU Mech. Bull. 1 68-80
[2] Pavliček N and Gross L 2017 Nat. Rev. Chem. 1 0005
[3] Bunkin N F, Gorelik V S and Filatov V V 2010 Phys. Wave Phenom. 18 90-5
[4] Moiseyenko V N, Brynza N P, Sal B A, Holze R and Gorelik V S 2018 Inorg. Mater. 54 1250-5
[5] Panfilov Y V, Kolesnik L L, Ryabov V T and Sidorova S V 2017 J. Phys.: Conf. Ser. 872 012010
[6] Sidorova S V, Pronin M A and Isaeva A A 2018 Int. Russ. Automation Conf. (RusAutoCon) (IEEE) 1-4
[7] Fan W, Chen M, Yang S and Wu L 2015 Sci. Rep. 5 12100
[8] Kuleshova V L, Panfilova E V and Prohorov E P 2018 Int. Russ. Automation Conf. (RusAutoCon) (IEEE) 1-5
[9] Diao J J, Hutchison J B, Luo G and Reeves M E 2005 J. Chem. Phys. 122 184710
[10] Meijer J 2012 Langmuir 28 7631-8
[11] Syritskii A B and Panfilova E V 2018 IOP Conf. Ser.: Mater. Sci. Eng. 443 012035
[12] Tamhane A C 2009 Statistical analysis of designed experiments: theory and applications 609 (John Wiley & Sons)