OPTICAL INFORMATION TECHNOLOGIES

Photo Extraction of Rubidium Atoms from the Bulk of a Photonic Crystal

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Abstract—The photo extraction of rubidium atoms from the bulk of a photonic crystal has been investigated. It has been found that in the case of irradiation of the crystal in the stop band where the desorbing light does not penetrate deeply, the separation of atoms occurs practically from its surface, so that the density of desorbed atoms in the cell decreases only exponentially. In the case of irradiation of the crystal outside the stop band, the bulk of the crystal is irradiated almost completely. In this connection, the exponential decrease in the density of atoms in the cell is replaced by its relatively slow reduction of diffusion nature. The bulk diffusion coefficient of rubidium atoms in the photonic crystal was measured to be $2 \cdot 10^{-8}$ cm^2/s.

Keywords: collision of atoms with surface, adsorption time, diffusion, diffusion coefficient of atoms in photonic crystal.

INTRODUCTION

It is well known that atoms and molecules can be adsorbed from a gas by a solid surface. The phenomenon opposite to adsorption is desorption of adsorbed particles from the solid surface to the gas. Particle desorption can be achieved by irradiating the surface with visible or UV light. In the latter case, this phenomenon is called the photodesorption of particles from solid surfaces.

Another effect is the absorption of particles in which they are captured but by the bulk rather than the surface of the absorber. A vivid example of absorption is the absorption of gases by activated carbon. It is interesting that until recently, researchers have not paid attention to the effect of particle extraction from the absorber bulk under the action of light, which can be regarded as the phenomenon opposite to absorption. Note that in the domestic and foreign literature, there is no term for this phenomenon.

In the foreign literature, there are a large number of papers devoted to the extraction of organic molecules from the bulk of an absorber heated by microwave radiation. As shown in [1, 2], the photo extraction of rubidium atoms and many molecular gases from the bulk of a polydimethylsiloxane (PDMS) film is not associated with the trivial heating of the medium. It has a more complex nature and can be regarded as the phenomenon opposite to absorption. Photo extraction of atoms and molecules from an absorber bulk is organically related to the subsurface diffusion of particles in the bulk. The bulk diffusion of particles, in turn, plays an important role in the interaction of particles with the surface. For example, it has been shown [3] that when an atom with thermal velocity collides with a glass surface, it can penetrate a great depth into it, return by diffusion after a while, and be desorbed from the surface. The total dwell time of the atom on the glass surface is determined by the diffusion time inside the glass, which leads to larger dwell time even in the case of low potential barrier on the surface and high temperature. Thus, the study of absorption and photo extraction of particles of various types by absorbers is an interesting and important task.

In this paper, we present the results of experimental studies of the photo extraction of rubidium atoms from a photonic crystal PC).
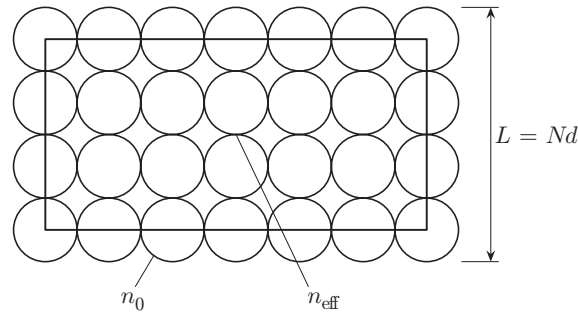
Fig. 1.

PHOTONIC CRYSTALS

Photonic crystals are materials whose structure is characterized by a periodically varying refractive index on a scale of the order of the wavelength. Due to this change in the refractive index, the spectrum of reflected electromagnetic waves or electromagnetic waves transmitted through the crystal has a banded pattern. Similarly to the forbidden energy gap for charge carriers in semiconductors, PCs allow obtaining stop bands. This implies that in a certain region of the spectrum, light is specularly reflected from the PC. Varying the light wavelength makes it possible to vary the reflection coefficient and the depth of light penetration into photonic crystals from zero to the total thickness of the crystal.

This offers a unique opportunity to desorb atoms either exclusively from the surface of a photonic crystal (photodesorption) or from the crystal bulk adjacent to the surface (photo extraction). For this, the crystal should be irradiated with a narrow-band radiation with a wavelength lying in the spectral region of the stop band or outside the stop band, thus switching the occurrence of two effects on the same object.

Often photonic crystals are made from monodisperse spherical silica particles (MSSPs). Figure 1 shows the particle structure in the photonic crystal.

The position of the stop band of the PC in the radiation transmitted through the crystal is described by the Wolfe–Bragg condition

$$\lambda = 2d\sqrt{n_{\text{eff}}^2 - \sin^2\psi}. \tag{1}$$

Here n_{eff} is the effective refractive index; ψ is the angle of incidence; d is the distance between the planes

$$d = 2r\sqrt{2/3}, \tag{2}$$

where r is the radius of the MSSPs. The effective refractive index is calculated by the formula

$$n_{\text{eff}}^2 = fn_{\text{SiO}}^2 + (1-f)n_{\text{air}}^2, \tag{3}$$

where $f = 0.74$ is the filling factor (the proportion of particles in the total bulk of the photocrystalline film); $n_{\text{SiO}} = 1.46$ is the refractive index of the MSSPs; $n_{\text{air}} = 1.0$ is the refractive index of air. Note that the reflection coefficient of such photocrystalline films in the region of the stop band can reach values of up to 90%, and the penetration depth can reach two to three layers [4].

One method to obtain a PC is the method of a moving meniscus (Fig. 2) [5]. Meniscus is the curvature of the liquid surface in the region of its contact with the solid surface. A glass substrate is placed at some angle in a solution of lyophobic MSSPs (not dissolving in a liquid). Crystallization of nanoparticles occurs when the meniscus moves as a result of evaporation of the liquid.

The thickness of the film is varied from 25 to 35 layers by changing the MSSP concentration in the solution. The MSSPs are acted upon by the forces of molecular attraction and electric repulsion and the gravitational force. Note that the growth of the PC occurs not in all solutions and can be accompanied by the formation of defects. A photograph of a cleavage of one of the photonic crystals is presented in Fig. 3. The image was obtained with a scanning electron microscope (Phenon XL SEM) and clearly shows closely packed and regular layers in the PC. All MSSPs have a relatively small spread in size, some amount of defects, and 15 layers.
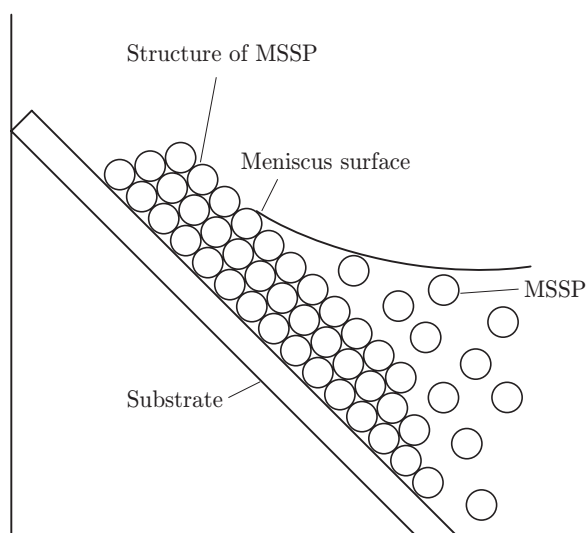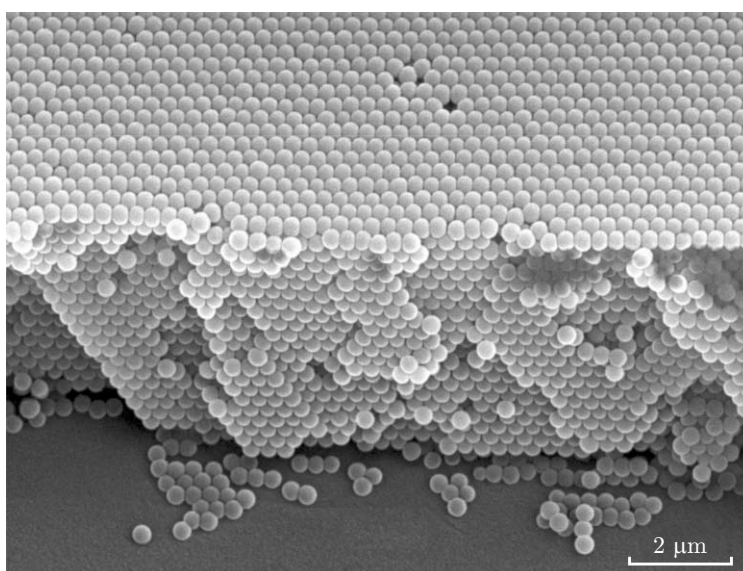
Fig. 2.

Fig. 3.

Figure 4 shows an example of the dependence of the transmittance of a PC of green color on wavelength. It can be seen that when the light is incident normally on the crystal surface, the transmission spectrum at $\lambda = 552$ nm has a clearly expressed minimum with a half-height width of 525 to 575 nm. When the crystal is inclined, this structure is shifted to the blue region. The dependence of the transmittance of the green PCs on wavelength was recorded using a Shimadzu 2501PC spectrophotometer. The wavelength of the stop band at normal incidence is 552 nm, which is confirmed by visual observation (the PC is green colored). Substitution of the wavelength of the stop band into the Wolfe–Bragg condition (1) for $\psi = 0$ yields a MSSP diameter $2r = 247$ nm, which is consistent with electron microscopic measurements.

EXPERIMENT

Figure 5 shows a schematic of the experimental setup, which includes a cell *1* and a diode laser *2* with a wavelength of 780 nm to excite the fluorescence of rubidium vapor. The cell was a tube with a diameter of 40 mm and a length of 500 mm consisting of two sections. In the first section, there was a small amount of metal rubidium, the inside of the second section was coated with a PDMS film, which prevented the absorption of atoms by the wall and thereby greatly increased the lifetime of atoms in the section and the
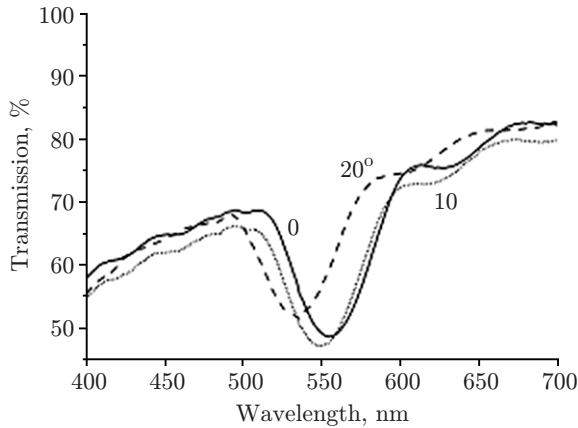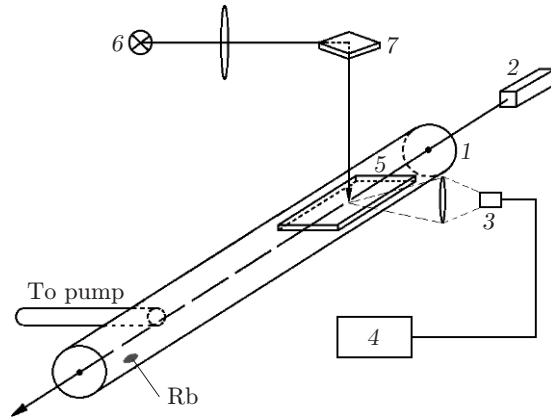
Fig. 4.

Fig. 5.

magnitude of the desorption signal. At the beginning of all the experiments, the PC 5 (equipped with a steel bracket mechanically fixed on the end face of the crystal) was at the end of the tube at some distance from both sections.

The density of desorbed Rb vapor was measured by detection of the atom fluorescence intensity by a photodiode 3, connected to a data acquisition system 4. The fluorescence of rubidium vapor was excited by an unstabilized diode laser 2 with a wavelength of 780 nm near the resonance transition of rubidium atoms. As an unstabilized laser was used, its frequency was periodically scanned around the absorption line of rubidium atoms using a triangular modulation of the laser pump current. This density measurement method allowed us to avoid the influence of the instability of the laser radiation frequency on the measurement results. Vapor density was determined from the averaged amplitudes of the spectral lines of rubidium isotopes. Fluorescent signals were processed with a data acquisition system consisting of a digital oscilloscope and a computer. Vacuum of up to 10^{-6} torr was maintained by a turbo pump. Residual gas pressure was measured using a vacuum gauge inside the exhaust cart. A stable level of vacuum in the cells was reached after a week of heating to 100 °C and a continuous evacuation of the residual gas. The desorbing light was obtained from a powerful (500 W) halogen 6 lamp with a condenser. Isolation of the required spectral region was made by means of a diffraction grating 7 (1500 lines/mm). The distance from the lattice to the PC was 5 m, which provided a sufficiently intense desorption radiation with a spectrum width of about 50 Å and about 14 desorption beams from 300 to 1000 nm.

The density of desorbed rubidium atoms was measured as follows. First, the PC was moved with an external magnet to saturate the surface with atoms in the first section with rubidium. For this, the section was heated to a temperature of 75 °C, which led to a partial pressure of Rb of about $4 \cdot 10^{-5}$ torr [6]. The saturation time was about 60 min. Note that the saturation of the crystal was carried out before each measurement. After that, the PC was moved to the section with the PDMS coating and irradiated with a halogen lamp. A diffraction grating isolated the spectral region in the radiation of the halogen lamp which irradiated the section with the PDMS coating. The desorbing light wavelength was selected by rotating the diffraction grating around the axis oriented along the vacuum tube. The initial absence of Rb in the desorption section was checked by irradiating the section without placing the photonic crystal in it. This provided a basis for asserting that the observed signals are due only to Rb atoms desorbed from the PC plate, and not to atoms desorbed from the cell walls. After saturation of the PC with rubidium vapor for 60 min, it was irradiated with light of constant intensity with the selected wavelength.

Figure 6 shows the time dependence of the density of desorbed rubidium vapor obtained using a constant light with a wavelength of 552 nm, which corresponds to photodesorption in the stop band. It can be seen from the figure that immediately after switching-on of the light at zero time, the vapor density due to photodesorption increases by a factor of 20 from the background value. After reaching the maximum, the density (during the entire irradiation) decreases exponentially and reaches its initial background value in 100 s.

Figure 7 shows the time dependence of the density of desorbed rubidium vapor irradiated by light with a wavelength of 650 nm, which corresponds to photodesorption outside the stop band. The dependence
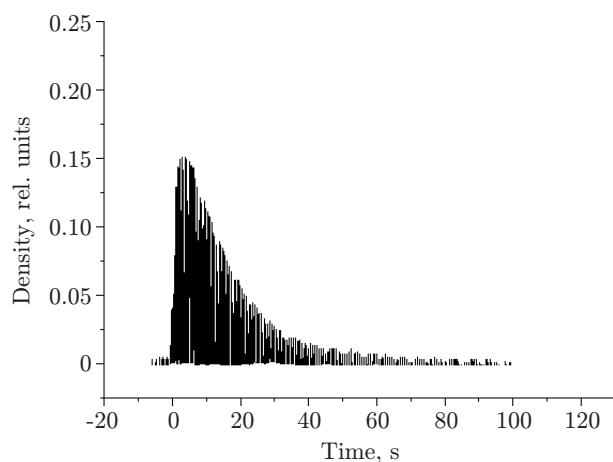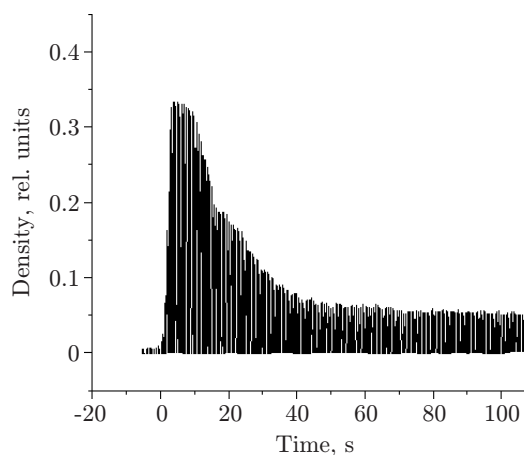
Fig. 6.

Fig. 7.

is normalized to the radiation power in the given spectral region. It can be seen that immediately after switching on the light, the vapor density due to photodesorption increases more significantly than in the case of photodesorption in the stop band (by a factor of 32 compared to the background value). After reaching the maximum, the density decreases exponentially and then slowly (with a typical time of about 7 min) decreases to a level 5–6 times higher than the original one. Such a striking difference in the behavior of both graphs is assumed to be due to the occurrence of two different effects during irradiation of the PC by desorbing radiation with wavelengths lying inside and outside the stop band.

In the case of photodesorption in the stop band, light, as noted above, does not penetrate deep into the crystal. Therefore, the separation of atoms as a result of photodesorption occurs practically from the surface of the crystal. After switching on constant light, the density of atoms in the cell increases due to photodesorption. Then, removal of Rb atoms from surface results in a decrease in their density and hence an exponential decrease in the density of desorbed atoms in the cell. The atoms in the depth of the crystal are not affected by the light, so that they do not contribute to the photodesorption signal.

In the case of using light with a wavelength outside the stop band, the bulk of the crystal is irradiated almost completely. Separation of atoms as a result of photodesorption occurs, as in the first case, from the surface of the crystal. The density of atoms in the cell increases because of photodesorption. Removal of atoms form the surface results in a decrease in their density and hence in an exponential decrease in the density of desorbed atoms in the cell, as in the first case. However, then the atoms deep in the crystal are involved in photodesorption and the exponential decrease in the density of atoms in the cell is replaced by a relatively slow decrease of diffusion character. Since the photodesorption outside the stop band involves practically all atoms, the photodesorption signal is much greater than in the first case.

The data obtained make it possible to estimate the diffusion coefficient of rubidium atoms in the photonic crystal, which is given by the expression $D = l^2/\tau$, where l is the thickness of the crystal and τ is the diffusion time. For a distance between the ICSS planes $d = 203$ nm and 15 layers, we have $D = 2 \cdot 10^{-8}$ cm^2/s. This value is much less than the diffusion coefficient for rubidium atoms in MSSPs measured in [7] $((1.2 \pm 0.7) \cdot 10^{-5}$ cm^2/s) and is less than the diffusion coefficient of rubidium in paraffin $(5 \cdot 10^{-7}$ cm^2/s) [8], despite the fact that the characteristic diameter of the channels between the spherical particles is relatively large even for close packing. Indeed, if the characteristic channel diameter is assumed to be equal to 1/20 of the diameter of the spherical particles $(d \sim 10$ nm), then for the case of Knudsen flow and a thermal velocity $\bar{v} = 2.7 \cdot 10^4$ cm/s, the expression $D = (d\bar{v})/3$ [3] gives a value of 10^{-2} cm^2/s for the diffusion coefficient, which is six orders of magnitude larger, than the measured value. Consequently, the free flight of atoms in the channels is accompanied by long dwell times on the MSSP surface, which do determine the small value of the diffusion coefficient of atoms in the photonic crystal. This conclusion requires a more detailed study of the diffusion process in the PC. Nevertheless, the experiments performed suggest that the diffusion of atoms in the crystal does not reduce to Knudsen diffusion in microporous solids.At the same time, it is far from the diffusion of vacancies that takes place in polymers.

CONCLUSIONS

In this paper, we presented the results of a study of the photo extraction of rubidium atoms from the bulk of a photonic crystal. It is shown that the detected photo extraction effect is due not only to the thermal heating of the crystal, but has a more complex and interesting nature.

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