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The way of photonic crystal formation in A^3B^5 and A^2B^6 semiconductors

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Abstract. It is shown that under influence of irreversible gigantic modification in monocrystalline A3B5 and A2B6 semiconductors, local areas with the highly changed refractive index are created. It was shown that a complex refraction index of CdS, CdTe and GaAs semiconductor samples after their modification was essentially changed. For example, the complex refraction index of CdS samples was changed from the magnitude $N = 2.75 + i2.8113$ up to the magnitude $N1 = 1.9 + i0.035$. In addition, the real and imaginary parts of a complex refraction index of CdS decrease, accordingly, by 0.85 and 2.7763. And its absorption index was 80-fold decreased. The theoretical analysis of experimental results has shown that quantum dots and quantum wires are responsible for such huge changes of the refractive index, which arise in modified areas of samples. It was shown that boundaries between modified and non-modified areas of the sample stretch down to the depth not less than 11 μm. It was shown that photon crystals with one-dimensionality and two-dimensionality can be effectively formed for visible and ultra-violet ranges without using the complex lithographical technique.

Keywords: photonic crystal, modification of semiconductors, irreversible gigantic modification

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1. Introduction

The newest methods of transfer, storage and processing information that are developed in hi-tech world centres of science are mainly based on researches in the field of physics of photonic crystals. It is considered that in future semiconductor optoelectronics they will find a lot of applications.

Photonic crystal (PC) is the optical medium where periodic alternation of areas with very differing magnitudes of the refractive index is artificially created. The period of refractive index changes is comparable with a light wavelength and exceeds considerably the period of a crystal lattice.

If the period of changes of the refractive index in such an optical medium in one, two or three directions (1D-, 2D-, 3D-photonic structures, accordingly) is comparable with an electromagnetic wavelength, then propagation of light in this medium cardinally differs from its propagation in usual medium.

Therefore, these artificial optical media are named as photonic crystals [1]. In PC the light from only specific ranges of the spectrum can propagate almost without absorption. These intervals of light wavelengths has received the name of "allowed photon zones". Similarly, the light wavelengths ranges out of which photons can not propagate in the optical transparent medium has received the name of the forbidden zone.

Photonic crystals are possible to be subdivided onto conductors, insulators, semiconductors and superconductors. Photonic conductors have the wide allowed photon zone (Fig. 1a), photonic insulators have the wide forbidden photon zone (Fig. 1b), photonic semiconductors have the narrow forbidden photon zone with the wide allowed photon zones (Fig. 1c) and photonic superconductors have a wide photon zone that coincides with the electronic forbidden zone (Fig. 1d). Those among PCs that can operate in visible and ultraviolet ranges, represent the greatest interest for semiconductor optoelectronics. However, because of very large technological difficulties in manufacturing PCs, up to date it was possible to make and investigate basically one- and two-dimensional PCs for the infrared region.

The authors [2] used high-quality photolithographical techniques and silicon technology for manufacturing PCs for the infrared region. On a wafer of monocrystalline silicon, formed was an auxiliary layer of SiO_2 where using the method of photolithography long parallel grooves we etched. Then these grooves were filled by polycrys-

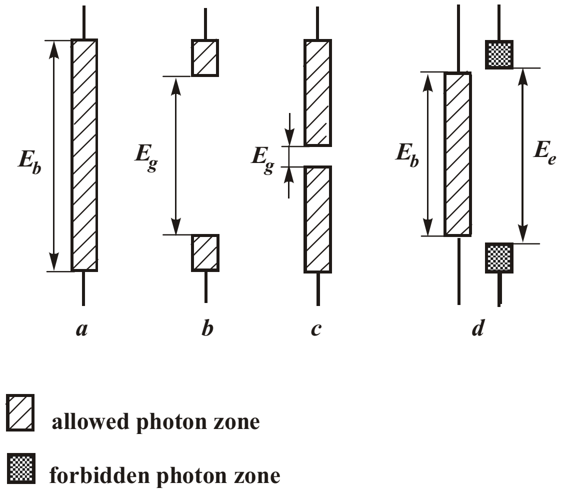

Fig. 1. Subdivision of photonic crystals onto photonic conductors, photonic insulators, photonic semiconductors and photonic superconductors.

talline silicon, and the plate was polished mechanically and chemically. The process was repeated, and in the second layer grooves were directed perpendicularly to the first ones. Using this difficult method, five layers were formed. Then the structure was immersed into fluoric acid, and all SiO_2 between silicon strings was etched. The generated bulk lattice consisted of a lot of silicon bars, each of them had 1.2 μm thickness, 1.5 μm height and 4.8 μm distances between silicon bars. The general thickness of PC was about 8 μm. The electromagnetic waves falling onto the plate perpendicularly to its surface were effectively reflected in the wavelength range 10–14 μm. Near a maximum of reflection (11 μm) PC missed less than 10 % of falling light energy.

2. Experimental setup and results

All those technological methods that change the refractive index of optical medium by very big magnitude (not less than 0.5) may be used for making PCs.

Earlier we have shown [3-5] that due to irreversible gigantic modification (IGM) it is possible to reduce the refractive index of semiconductor samples by the magnitude 0.5–0.8 (Fig. 2). As it follows from our work [3] using light, it is possible to create periodically alternating areas with very big magnitude of change of the refractive index in subsurface layers of semiconductor samples. However, in papers [3-5] the maximal depth of modification of a semiconductor sample was not determined, and the capability to form PCs due to IGM was not declared hence. It is obvious that depth of modification of a semiconductor will determine thickness of PC. The difference of the refractive indexes (or a gradient in a transitive layers) of the modified areas and non-modified areas will determine optical parameters of PCs.

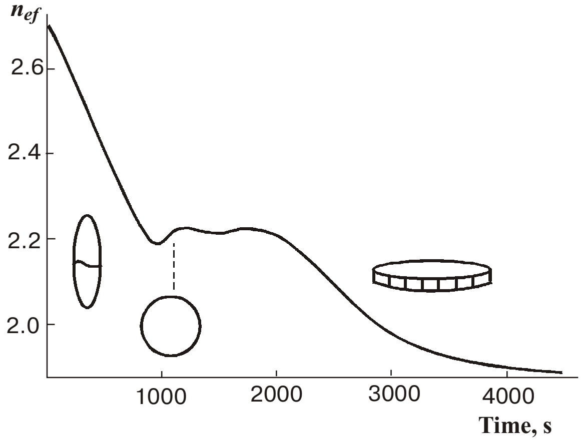

Fig. 2. Dynamics of changes of the refractive index real part in the near-surface region of CdS sample.

The study of movement dynamics for boundaries of the modified area and the depth of modification for CdS, CdTe and GaAs samples as well as development of a technique for manufacturing PCs were aims of this work.

In Fig. 3 shown is the experimental setup used for modification of samples by a light periodic field with the various periods (from 0.3 up to 10 μm).

Dynamics of intensity changes for light reflected into the plus-first reflection order from an arising periodic structure for the wavelength 0.4416 μm was used by us for determination of thickness (or depth) of the modified area of a monocrystal and magnitudes of its complex refractive index changes at these depths.

It was noticed by us experimentally that dynamics of changes in the diffraction efficiency of the formed gratings depends on the magnitude of the angle α (α – angle between a normal to the surface of the sample and a line of symmetry of our recording scheme). Dynamics of the dif-

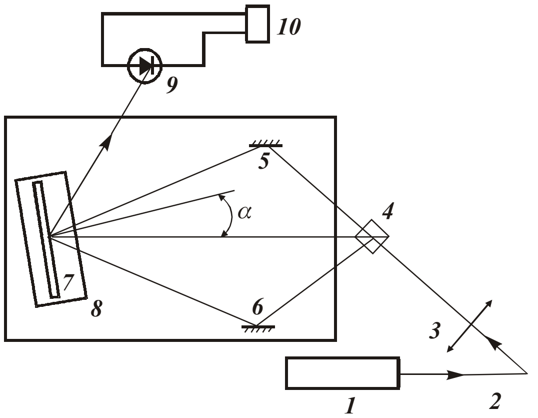

Fig. 3. Experimental setup for formation of photon crystals in semiconductor samples. *1* – He-Cd-laser with the wavelength 0.4416 μm, *2*, *5* and *6* – dielectric mirrors, *3* – lens, *4* – beam-splitting cube, *7* – semiconductor sample, *8* – cell with distilled water, *9* – photodiode, *10* – recording computer.

fraction efficiency of gratings formed on CdS, CdTe and GaAs samples at $\alpha = 20°$ and $\alpha = 0°$ are shown in Fig. 4. One can see that they have qualitative differences. In Fig. 4 one can see clearly maxima and minima of interference. For appearance of such interference, it is necessary for the light interference beams (a beam 1 and a beam 2) to have comparable intensity, and for their phases difference to be multiple to 2π (for maxima) or $\pi/2$ (for minima). For definiteness we shall name the beam reflected from the sample surface as the beam 1 and the beam reflected from the medium boundary of modified and non-modified areas as the beam 2.

In [4] it was shown that long quantum wires located perpendicularly to a surface of a sample in subsurface areas of a sample in the course of its modification arose. These quantum wires are formed of the charged dot defects of a semiconductor sample. The quantum wires arising in a matrix of a sample very strongly reduce its refraction index (by 0.5–0.8) that creates sharp jump of a refraction index at the medium boundary (MB) between the already modified and non-modified areas. Therefore, intensity of a reflected from this BD light (beam 2) has the magnitude comparable with intensity of a light reflected from a surface of the sample (beam 1). In Fig. 5, schematically shown is the sample modified only in those places where maxima of intensity of an interference picture and distribution of the refraction index in the cross-sectional view of a sample take place. Obviously, if the difference of refraction indexes between the already modified area and non-modified one exceeds 0.5, and the depth of a sample modification exceeds 5–8 μm, then such artificial optical medium represents a photonic crystal.

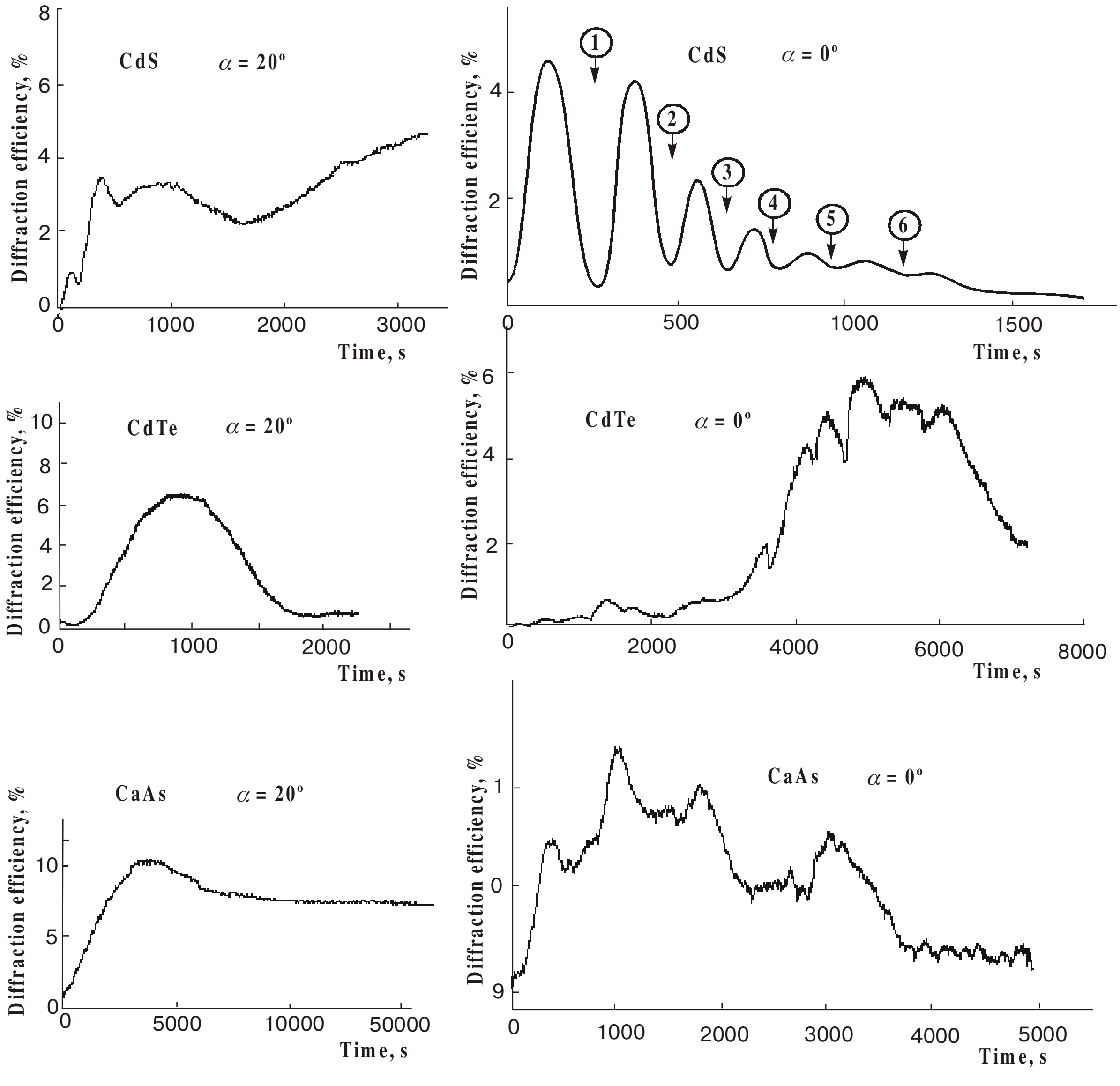

Fig. 4. Dependencies of diffraction grating efficiency at the first diffraction order during their recording in the surface region of semiconductors at angles $\alpha = 20°$ and $\alpha = 0°$ for CdS, CdTe and GaAs samples (with 1.8 μm grating period).

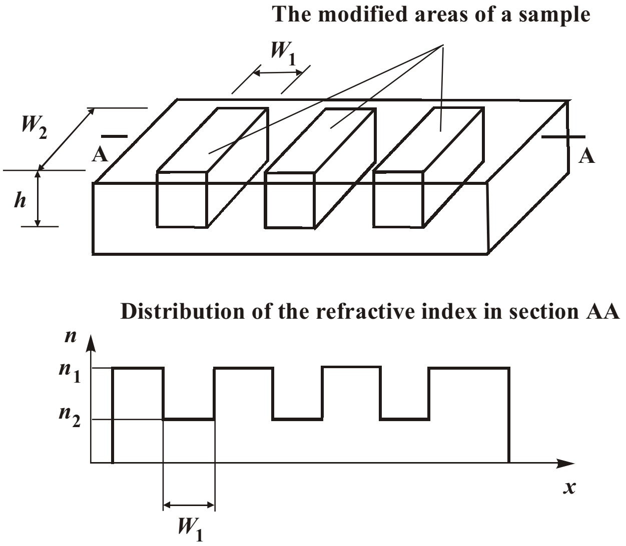

Fig. 5. Sample after modification. Distribution of the refractive index in the section A-A.

In the course of a sample modification, lengths of quantum wires are gradually augmented, and MB deepens into a sample. The beams 1 and 2, which form the plus-first reflex are reflected by the surface and MB, accordingly. During modification, the refraction index and thickness of the modified sample bulk are changed. Therefore, the phase of the beam 2 and its intensity are changed, too. Because of an interference of beams 1 and 2, maxima and minima appear on the plots of reflected light intensity dependence (we mean the intensity of the plus-first reflex). Magnitudes of refraction indexes in minima and quantity of such minima enabled us to determine both thicknesses and magnitudes of complex refraction indexes of the sample modified areas.

3. The theoretical analysis

The difference of phases d between beams 1 and 2 is equal $2\delta = 2(2\pi / 1)\cdot hn_2\cos\theta + \pi + \pi$. Here $\lambda = 0.4416$ µm is the wavelength of laser radiation in vacuum, h and n_2 are the thickness and refraction index of the modified area of medium, respectively, π – shift of a phase of light reflected from the top surface of a monocrystal and π – shift of a phase of light reflected from the boundary of media with refraction indexes n_2 and n_1 ($n_2 < n_1$). In our case the corner θ is small ($\cos\theta \sim 1$) therefore $2\delta = 2\,(2\pi / 1)\cdot(hn_2)$.

The reflection coefficient of the modified medium is equal [6]:

$$R = [R_{12} + R_{23} + 2(R_{12})^{1/2}(R_{23})^{1/2}e^{2\beta}\cos 2\delta] / [1 + R_{12}R_{23} + 2(R_{12})^{1/2}(R_{23})^{1/2}e^{2\beta}\cos 2\delta].$$

Here $R_{12} = [(n_2 - 1.33)^2 + \beta^2] / [(n_2 + 1.33)^2 + \beta^2]$, $R_{23} = [(n_1 - n_2)^2 + \beta^2] / [(n_1 + n_2)^2 + \beta^2]$, $\beta = \alpha\lambda/4\pi$, n_2 is a refraction index of a sample modified area, n_1 – a refraction index of a non-modified area of the sample, α – an absorption index of a sample. In the plots of dependences for reflection coefficients of CdS, CdTe and GaAs monocrystals during their modification one can see interference effects. Especially clearly seen is this interference in the plots of CdS monocrystal. In Fig. 4, one can see that in minima the magnitudes of the reflection coefficients are practically equal to zero (in the first minimum $R_{\min} = 0.00373$, in the second, third, fourth and fifth minima $R_{\min} \approx 0.006$). Therefore, all calculations of the reflection coefficients we produced for CdS monocrystals. In minima $\cos 2\delta = -1$. The magnitudes of the reflection coefficient in minima were determined by expression

$$R_{\min} = [R_{12} + R_{23} - 2(R_{12})^{1/2}(R_{23})^{1/2}e^{2\beta}] / [1 + R_{12}R_{23} - 2(R_{12})^{1/2}(R_{23})^{1/2}e^{2\beta}].$$

Using this expression we calculated dependence $R_{\min}$ from the magnitude of a refraction index of the modified area with various magnitudes of its absorption index (Fig. 6). In Fig. 6 one can see that in minima the reflection coefficients achieve the magnitudes 0.0047 and 0.009, accordingly. The magnitudes of imaginary parts of the complex refraction index equal to 0.035 and 0.07, respectively. In addition, the absorption index of the modified areas equal 10^4 and $2\cdot10^4$ cm^{-1}, accordingly. In both cases, the real parts of the refraction index are equal to 1.9 in their magnitudes. We may write down the magnitudes of the complex refraction index of the modified monocrystal CdS at the wavelength 0.4416 µm for those time moments when the reflection coefficients achieve the first, second, third, fourth and fifth minima, accordingly, as $N_1 = 1.9 + i0.035$ and $N_2 \approx N_3 \approx N_4 \approx N_5 = 1.9 + i0.07$. The complex refraction index of CdS monocrystal (before modification) at the wavelength 0.4416 µm was equal $N = 2.75 + i2.8113$. Thus, one can see that at the modification of CdS monocrystal both real (by 0.85) and imaginary (by

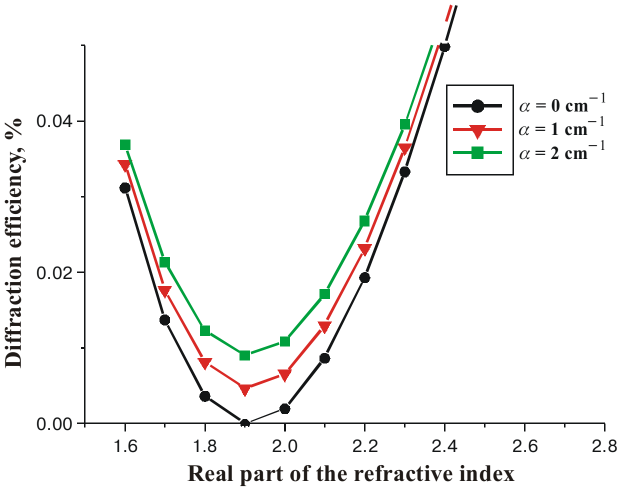

Fig. 6. Dependence $R_{\min}$ from the magnitude of a refraction index of the modified area at various magnitudes of its absorption index.

2.7763) parts of a complex refraction index reduce. One can see also that at modification the absorption index is 80-fold decreased.

The thickness of the modified area is equal to $h_{\min} = (2\delta\lambda)/(4n_2)$. The eighth minimum was achieved at $2\delta = 15\pi$. We have $h_{\min} = 0.8715$ µm. The measurement of modification thickness by this method becomes impossible after the eighth minimum of reflection intensity.

The measurements of the modification depth for the sample using the above interference method was limited by the magnitude 0.8715 µm because of a very great decrease of the refraction index in subsurface areas of a semiconductor sample at its modification and a very great decrease of reflected light intensity. Therefore, measurements of the large modification depths we made using a microscope. For measurements we used the intensive reflection of visible light from boundary of media between the already modified and non-modified areas. In these experiments a few monocrystal samples of CdS were modified for a various time intervals. For modification it was used an interference field of a light with the period 4 µm. We established experimentally, what depth of HD linearly increases with time of modification and we could confidently register its position up to the magnitude about 11 µm.

4. Conclusions

It was shown that a complex refraction index of CdS, CdTe and GaAs semiconductor samples was very considerably changed after their modification. For example, the complex refraction index of CdS samples was changed from the magnitude $N = 2.75 + i2.8113$ down to the magnitude $N1 = 1.9 + i0.035$. In addition, the real and imaginary parts of a complex refraction index of CdS were decreased accordingly by 0.85 and 2.7763. And its absorption index was 80-fold decreased.

It was shown that boundary of media division (between the already modified and non-modified areas of a sample) stretched down to the depth not less than 11 µm.

It was shown that the one-dimensional and two-dimensional photon crystals can be effectively formed for visible and ultra-violet ranges of light without using complex lithographical techniques.

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