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Optical properties of quantum-sized structures and two-dimensional photon crystals fabricated in semiconductor substrates using irreversible giant modification

A.M.Kamuz, P.F.Oleksenko, O.A.Kamuz, O.A.Ilin, A.V.Stronski

V.Lashkaryov Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, 41 Nauki Ave., 03028 Kyiv, Ukraine

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It is known that using the irreversible giant modification, it is possible to change locally the refractive index of semiconductors. This work is concerned with the development of the methods of photonic crystal formation basing on CdS, CdTe and GaAs semiconductors. It was shown that complex refractive index of the CdS, CdTe and GaAs semiconductor samples is changed significantly after their modification. For example, the complex refractive index of CdS is changed from $2.75 + i2.8113$ up to $1.9 + i0.035$. The real and imaginary parts of CdS refractive index are decreased by 0.85 and 2.7763, respectively, while the absorption coefficient is decreased by 80 times. It is also shown that the interface between modified and non-modified sample areas is submerged into the sample depth (the distance from the surface being at least 11 μm). Thus, one- and two dimensional photonic crystals for visible and ultraviolet ranges can be effectively obtained using CdS, CdTe and GaAs semiconductor substrates by modifying thereof without complex lithographic technology.

Известно, что с помощью необратимой гигантской модификации можно локально изменять коэффициент преломления полупроводников. Настоящая работа посвящена разработке методики формирования структур фотонных кристаллов в полупроводниковых материалах CdS, CdTe и GaAs. В работе показано, что комплексный показатель преломления в полупроводниках составов CdS, CdTe и GaAs претерпевает значительные изменения после вышеупомянутой модификации. Для CdS комплексный коэффициент преломления изменяется от величины $2{,}75 + i2{,}8113$ до $1{,}9 + i0{,}035$. Действительная и мнимая части комплексного коэффициента преломления CdS уменьшаются на 0,85 и 2,7763 соответственно, а коэффициент поглощения уменьшается в 80 раз. Также показано, что граница раздела между модифицированным и не модифицированным участками находится под поверхностью образца, на глубине не менее 11 мкм. С применением такого способа модификации оптических свойств полупроводников можно изготавливать одно- и двумерные фотонно-кристаллические структуры для видимого и ультрафиолетового диапазонов на полупроводниковых подложках составов CdS, CdTe и GaAs без использования сложных многоступенчатых литографических технологий.

It is believed that photonic crystals will find a wide application in information processing, storage, and transfer [1–5]. A photonic crystal (PC) is an optical medium where periodically alternating areas with different refractive indices $(n_{max} - n_{min}) > 0.5$, where n_{max} and n_{min} are refractive indices of the periodically alternating areas) are formed. The refractive index change period is comparable with the light wavelength and is substantially larger than that of the crystalline lattice one. If the refractive index change period in a medium in one-, two-, or three-dimensional structures (1D-, 2D-, 3D-photonic structures) is comparable with the electromagnetic wavelength, then the light propagation differs from that in an ordinary medium. That is why such artificial media are referred to as photonic crystals [1–5]. In PC, only light waves of certain wavelengths can propagate, thus, allowed and forbidden photon bands (zones) exist in PC. Of most interest for semiconductor optoelectronics are the PC active in visible and ultraviolet spectral ranges. At present, there are no preparation methods of such PC.

Any technological methods suitable to change locally refractive index of a medium by a considerable value (at least by 0.5) can be used for the PC preparation. It has been shown by us before [6–8] that using the irreversible giant modification (IGM), it is possible to change locally the refractive index of a semiconductor by 0.5–0.8. It followed from our work [6] that using light, it is possible to form local periodically alternating areas differing considerably in refractive index within the sample subsurface layers. But in [6–8], the maximum depth of the semiconductor sample modification by IGM was not determined and thus the PC formation possibility by IGM was not demonstrated. It is obvious that the semiconductor sample modification depth will define the PC thickness, and the refractive index difference (or gradient in the transition layer) between modified and initial areas will define its parameters. The aim of this work is to study the movement dynamics of the modified area boundary and the modification depth of the CdS, CdTe and GaAs semiconductor samples and to develop the PC formation methods using IGM.

The periodic light interference pattern (which was formed on the surface of a semiconductor sample as shown in Fig. 1) with different periods (from 0.3 up to 10 μm) was used. Dynamics of the intensity change of the reflected light into +1-st reflex from the appearing periodic structure at wavelength was used to determine the thickness (depth) of the modified single crystal area and values of its complex refractive index at these depths. It was shown in experiment that the dynamics of the diffraction efficiency change in the forming gratings depends on α (α being the angle between normal to the sample surface and the symmetry line of the recording scheme).

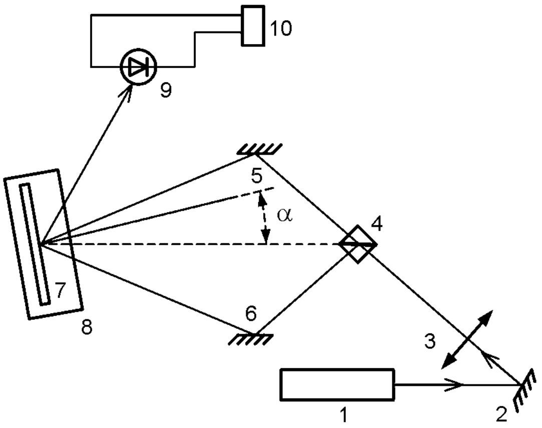

Fig. 1. 1, He–Cd laser with 0.4416 μm wavelength; 2, 5, 6, dielectric mirrors; 3, lens; 4, beamsplitter; 7, semiconductor sample; 8, cell with bidistilled water; 9, photodiode; 10, recorder.

The diffraction efficiency evolution in the gratings formed on CdS, CdTe and GaAs samples at $\alpha = 20^\circ$ and $\alpha = 0^\circ$ is shown in Fig. 2. Those are seen to be qualitatively different. In Fig. 2, the interference maxima and minima are clearly seen. For such interference, it is necessary that interfering light fluxes (flux 1 and flux 2) will be comparable in intensity and their phase differences were divisible by 2π (maxima) or $\pi/2$ (minima). For certainty, we will note the flux (beam) reflected from the sample surface as flux 1, and flux reflected from the interface of modified and non-modified areas as flux 2.

It was shown [7] that under IGM, long quantum wires oriented perpendicular to the sample surface are formed in the sample subsurface area. These quantum wires are formed from the charged defects of the semiconductor sample. Quantum wires formed in the sample matrix decrease considerably its refractive index (by 0.5–0.8), which results in a sharp leap of the refractive index at the interface between modified and non-modified areas. Thus, the intensity of the light reflected from this interface (flux 2) is comparable to the light intensity reflected from the sample surface (flux 1). In Fig. 3, the sample modified locally only in such places where maxima and minima of the interference pattern are positioned is shown schematically; shown is also the refractive index distribution in the sample cross-section. It is obvious that if the refractive index difference between the non-modified and modified areas exceeds 0.5

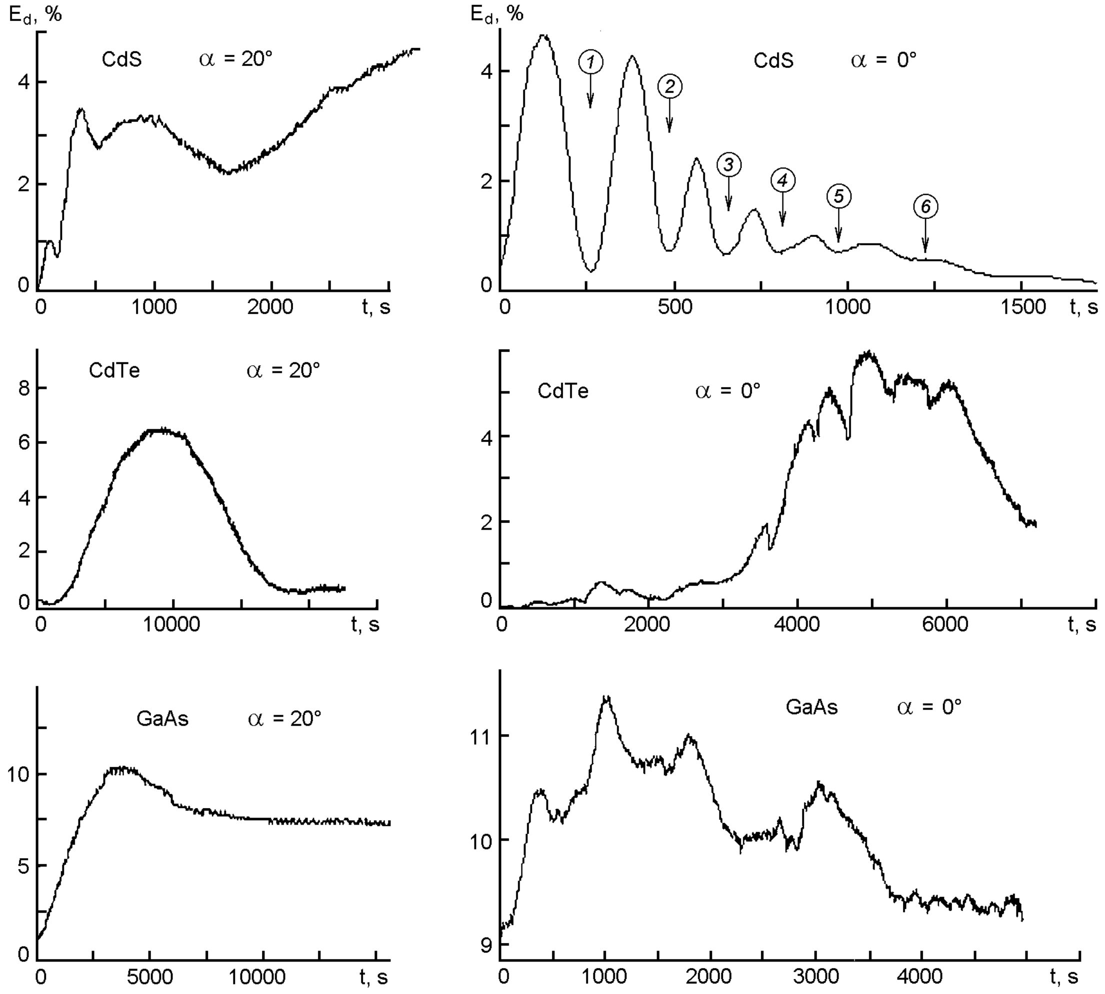

Fig. 2. Dependences of grating diffraction efficiency at the first diffraction orders during their recording in the surface region of semiconductors at angles $\alpha = 20°$ and $\alpha = 0°$ for CdS, CdTe and GaAs samples (with 1.8 μm grating period).

and the sample modification depth exceeds 5–8 μm, such artificial medium is a photonic one.

During the sample modification, the quantum wires are gradually enlarged and interface is submerged into the sample depth. From crystal surface and from interface are reflected, respectively, fluxes 1 and 2, which form +1-st reflex. Because the refractive index and the thickness of the modified area are changed during modification, the phase and intensity of the flux 2 are changed. Due to interference of the 1 and 2 fluxes, maxima and minima appear in the reflected light dependence (the +1-st reflex intensity). Values of the reflection coefficient in minima and the number of such minima enabled us to determine the thickness as well the values of the complex refractive indices of the modified sample areas.

The phase difference δ between fluxes 1 and 2 is $2\delta = 2\cdot(2\pi/\lambda)\cdot[hn_2\cos(\theta)] + \pi + \pi$. Here $\lambda = 0.4416$ μm is the laser radiation wavelength in vacuum; h, thickness and n_2, refractive index of the modified area, respectively; π, the phase shift of light reflected from interface between media with refractive indices n_2 and n_1 ($n_2 < n_1$). In our case, angle θ is small ($\cos(\theta) \sim 1$), thus, $2\delta = 2\cdot(2\pi/\lambda)\cdot hn_2$.

The reflection coefficient of the modified medium is [9]:

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

Here

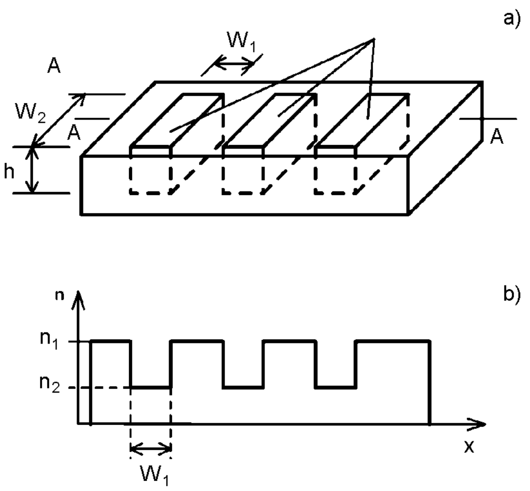

Fig. 3. Modified areas of sample (a). Refractive index profile in A–A cross-section (b).

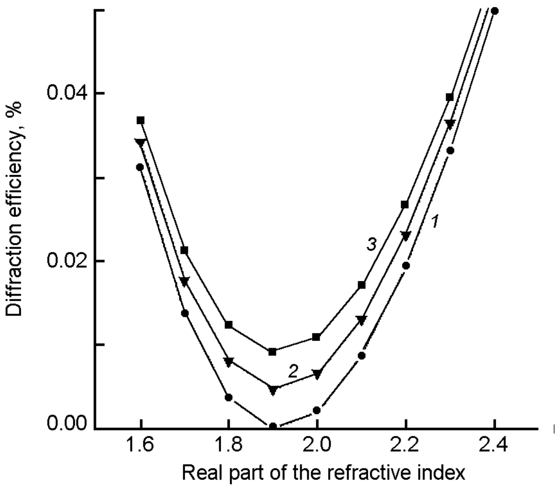

Fig. 4. Diffraction efficiency (%) vs real part of the refractive index: α, cm^{-1} = 2 (*1*), 1 (*2*), 0 (*3*).

$$R_{12} = \frac{(n_2 - 1.33)^2 + \beta^2}{(n_2 + 1.33)^2 + \beta^2},$$

$$R_{23} = \frac{(n_1 - n_2)^2 + \beta^2}{(n_1 + n_2)^2 + \beta^2}, \ \beta = \frac{\alpha\lambda}{4\pi};$$

n_1, refractive index of the sample non-modified area, α, the sample absorption coefficient. Interference effects are seen in the reflection coefficient dependences of the CdS, CdTe and GaAs single crystals at their modification. An especially clear interference is seen in the reflection coefficient dependence of CdS single crystal. It is seen from Fig. 2 that in minima, the reflection coefficient values are essentially equal to zero (in first maximum, R_{min} = 0.00373, in second, third, fourth and fifth ones, $R_{min} \approx 0.006$). Thus, all reflection coefficient calculations were performed for CdS single crystal. In minima, $\cos(2\delta) = -1$. The reflection coefficients values of the in minima are given by expression

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

Using this expression, we have calculated dependence of R_{min} on the refractive index of modified area at different values of its absorption coefficient (Fig. 4). It is seen from Fig. 2 that in minima the reflection coefficients reach 0.0047 and 0.009, respectively, the imaginary parts of complex refractive index being 0.035 and 0.07, respectively. The absorption coefficients of the modified areas are 10^4 cm^{-1} and $2\cdot10^4$ cm^{-1}, respectively. The real parts of refractive index in both cases are 1.9. This enables to write the complex refractive index values for the modified CdS single crystal for the wavelength 0.4416 µm for time moments when reflection coefficient reaches first, second, third, fourth and fifth minima, respectively, 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 refractive index of the non-modified CdS single crystal at the wavelength 0.4416 µm is $N = 2.75 + i2.8113$. Thus, it is seen that at modification of the CdS single crystal, the real and imaginary parts of the complex refractive index are decreased (by 0.85 and 2.7763, respectively). It is also seen that due to modification, absorption coefficient is decreased by 80 times.

The modified area thickness is $h_{min} = 2\delta\lambda/4n_2$. Eighth minimum is achieved at $2\delta = 15\pi$. We have h_{min} = 0.8715 µm. After eight minima of the reflex intensity, it is impossible to measure the modification thickness by this method.

Measurements of the sample modification depth using interferometry are limited to the value of 0.8715 µm, because due to the refractive index decrease of the semiconductor sample surface areas, the reflected light intensity is decreased and it is impossible to record more than 7–8 minima. Thus, the measurements of the larger modification depths was carried out using a microscope. It was also taken into account that the intense light reflection of visible range from interface is easy to record using a microscope. In these experiments, several samples of CdS single crystals were modified at various exposures. For the modification the light interference pattern with 4 μm period was used. After modification, the interface depth was measured, which has the same period 4 μm. It was established that the interface depth was linearly increased with the modification duration, and its position was confidently registered up to the value ~11 μm.

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Оптичні властивості квантово-розмірних структур та двовимірних фотонних кристалів, виготовлених у напівпровідникових субстратах за допомогою незворотної гігантської модифікації

О.М.Камуз, П.Ф.Олексенко, О.О.Камуз, О.О.Ільїн, О.В.Стронський

Відомо, що за допомогою незворотної гігантської модифікації можна локально змінювати коефіцієнт заломлення напівпровідників. Ця робота присвячена розробці методики формування структур фотонних кристалів у напівпровідникових матеріалах CdS, CdTe і GaAs. Показано, що комплексний показник заломлення у напівпровідниках CdS, CdTe і GaAs значно змінюється після вищезгаданої модифікації. Для CdS комплексний коефіцієнт заломлення змінюється від величини $2{,}75 + i2{,}8113$ до $1{,}9 + i0{,}035$. Дійсна та уявна частини комплексного коефіцієнта заломлення у CdS зменшуються відповідно на 0,85 і 2,7763, а коефіцієнт поглинання зменшується у 80 разів. Також показано, що границя розділу між модифікованими та немодифікованими ділянками знаходиться під поверхнею зразка, на глибині щонайменше 11 мкм. Із застосуванням такого способу модифікації оптичних властивостей напівпровідників можна виготовляти одно- та двовимірні фотонно-кристалічні структури для видимого і ультрафіолетового діапазонів на напівпровідникових субстратах зі сполук CdS, CdTe і GaAs без використання складних багатоступінчастих літографічних технологій.