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Photorefractive multiple quantum wells planar waveguide

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Abstract

New type of planar optical waveguide with a guiding layer consisting of photorefractive multiple quantum well structure is investigated. Results of optical and electro-optical measurements and possible applications for all-optical switching of guided signals are presented.

Keywords: nonlinear waveguide, photorefractive multiple quantum wells, all-optical switching.

Światłowód planarny z warstwą fotorefrakcyjnych studni kwantowych

Streszczenie

Opisano nowy rodzaj światłowodu planarnego o warstwie prowadzącej zawierającej fotorefrakcjne studnie kwantowe. Przedstawione są wyniki pomiarów własności optycznych i elektro-optycznych układu oraz pokazane możliwości zastosowania do całkowicie optycznego przełączania sygnałów propagujących się w światłowodzie.

Słowa kluczowe: nieliniowe światłowody, fotorefrakcyjne studnie kwantowe, całkowicie optyczne przełączanie.

1. Introduction

Photorefractive effect is usually defined as the light-induced change of the refractive index, which occurs in some electro-optic materials in the case of nonuniform illumination. The effect includes photogeneration of free carriers, their transport and recombination to traps, what leads to appearing of a space-charge electric field. The electric field changes the refractive index of material through an electro-optic effect. Semi-insulating quantum well structures are specific photorefractive media. Their wavelength dependent electro-optic properties are strongly enhanced in the range of exciton transitions [1, 2]. Compared with other photorefractives multiple quantum well (MQW) structures have high sensitivity and short response time (approximately microseconds), what makes them promising for applications in electro-optics devices, like optical switchers or light modulators. The photorefractive properties of MQW's have been investigated theoretically since early 90's [3] and demonstrated experimentally in a number of applications [4].

Because of the large absorption of light associated with the near resonant wavelength, thin layers (typically 1 to 2 μm) of PR-MQW work usually in a transmission geometry where light beams pass across the structure. If the sample is biased with an external electric field applied parallel to the quantum well layers (so called Franz-Keldysh geometry) the electro-optic effect relies on broadening of exciton peaks existing in absorption spectrum. The near resonant absorption spectrum calculated for $GaAs/Al_{0.3}Ga_{0.7}As$ multiple quantum well structure at room temperature is shown in Fig. 1. The dashed line describes the sample placed in the external field of 10 kV/cm and a solid line the sample without the field. The field induced changes in absorption spectrum are accompanied by refractive index changes.

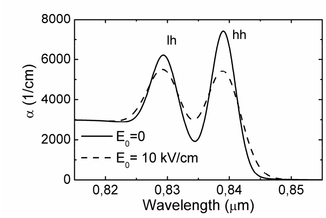

Fig. 1. The absorption spectrum of biased and unbiased PR-MQW structure, calculated for the typical MQW parameters [2]. The peaks correspond to creation of heavy hole (hh) and light hole (lh) excitons. The continuous contribution is due to the creation of free electron – hole pairs

Rys. 1. Widmo absorpcyjne struktury PR-MQW w polu elektrycznym i bez pola obliczone dla typowych wartości parametrów MQW [2]. Piki odpowiadają generacji ekscytonów z ciężkimi dziurami (hh) i lekkimi dziurami (lh). Widmo ciągłe związane jest z generacją swobodnych par electron-dziura

In contrast to all previous applications we study here the geometry proposed by our group [5], with PR-MQW structure used as a guiding layer of planar waveguide. Waveguide geometry gives new possibilities like all-optical steering of guided modes propagation with the help of external waves (Fig. 2) or photorefractive solitons propagation [6]. The first case is a combination of the waveguide configuration with the transmission geometry. Two external mutually coherent beams interfere inside the MQW layer creating the intensity pattern described by

$$I(x,z) = I_0(x)[1 + m\cos(Kz)], \qquad (1)$$

where $I_0 = I_{w1} + I_{w2}$ is the total light intensity of the beams, and $m = 2(I_{w1}I_{w2})^{1/2}/I_0$ denotes the modulation index (the fringe contrast).

The periodic light distribution (1) transforms into periodic changes of the refractive index (so called photorefractive grating). The grating can influence signal wave propagating in the waveguide leading to selective reflection, deflection, coupling or change of the polarization state [7]. On the contrary to traditional waveguide gratings with constant parameters optically induced gratings are adjustable. The grating parameters can be modified by changes of the incident angle and intensity of the external waves, what can lead to optical steering of the signal guided along the MQW layer. An additional advantage of the proposed structure is its compatibility with other integrated optics devices.

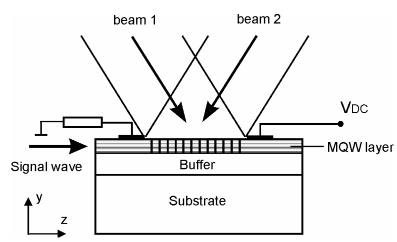

Fig. 2. The photorefractive MQW waveguide with two mutually coherent external waves creating a photorefractive grating which can influence propagation of the signal wave

Rys. 2. Światłowód z warstwą prowadzącą składającą się z fotorefrakcyjnych studni kwantowych. Dwie wzajemnie spójne fale zewnętrzne generują siatkę fotorefrakcyjną, która może wpływać na propagację fali sygnałowej

2. Multiple quantum well waveguides structure

To investigate propagation properties of PR-MQW waveguides we designed two types of samples. The waveguides were fabricated in the Institute of Electronic Materials Technology (ITME) in Warsaw by metal-organic-chemical-vapour-deposition (MOCVD) method. Both structures (see Fig. 3) have the same MQW guiding layer which consists of 60 periods of alternating 10 nm GaAs and 7.5 nm $Al_{0.3}Ga_{0.7}As$ layers.

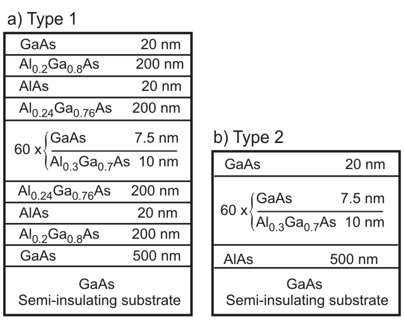

Fig. 3. Schemes of multiple quantum well wafers used in measurements. Sample of type 1 is designed to enable etching of the substrate

Rys. 3. Struktury wielokrotnych studni kwantowych użyte w badaniach. Próbka typu 1 zaprojektowana została w taki sposób, aby umożliwić wytrawienie podłoża

In both cases growth begins with 500 nm buffer layer (GaAs in type 1, and AlAs in type 2), which is grown on semi-insulating GaAs substrate. The first type of the samples was designed to make absorption and electro-absorption measurements possible. This can be attained in transmission geometry [1], requiring the substrates to be removed through etching process. Therefore in such structures, MQW guiding region is surrounded by 200 nm $Al_{0.24}Ga_{0.76}As$ cladding layer and two stop-etch layers 20 nm AlAs and 200 nm $Al_{0.2}Ga_{0.8}As$. In the second type of samples, MQW layers are grown directly on buffer layer which performs a function of the cladding.

After growth, wafers of both types were cleaved and proton implanted to provide appropriate concentration of deep-level traps, which is requisite to make structure semi-insulating. The results of dark resistivity measurements (about 10^7 Ω·cm) confirmed the semi-insulating properties of the samples. Complete devices were fastened to glass slides and placed on mounting stands. In the final stage, the electrodes were placed on the top layers. Two scanning electron microscope (SEM) images of the sample of type 2 are shown in Fig. 4.

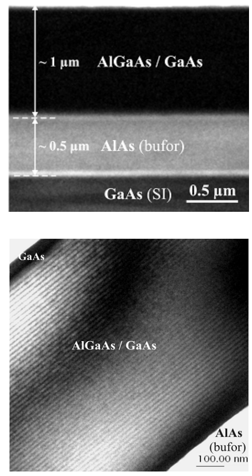

Fig. 4. SEM images of the waveguide of type 2. In the upper figure a structure of the waveguide is shown, whereas in the lower figure an image of GaAs/AlGaAs guiding layer is presented

Rys. 4. Obrazy SEM falowodu typu 2. Na górnym rysunku pokazano strukturę falowodu, a rysunek dolny przedstawia obraz warstwy prowadzącej

3. Electroabsorption and Electrorefraction

The structures of the first type were used in transmission experiments performed with static electric fields. The field dependent absorption was calculated from the simple dependence:

$$\Delta\alpha(\lambda,E) = -\frac{1}{L}\ln\left[1+\frac{T(\lambda,E)-T(\lambda,0)}{T(\lambda,0)}\right],$$

where $T(\lambda, E)$ describe experimentally obtained transmission spectra and L is the thickness of the sample. The changes in absorption spectrum evoked by electric field of intensities 1 kV/cm, 2 kV/cm and 3 kV/cm are depicted in Fig. 5a. The changes in refractive index calculated through Kramers-Krönig relation [8]:

$$\Delta n(\lambda) = \frac{\lambda^2}{2\pi^2} P\int_0^{\infty} \frac{\Delta\alpha(\lambda')}{\lambda^2-\lambda'^2}d\lambda',$$

are shown in Fig. 5b.

The photorefractive grating can be recorded with photon energy larger than the bandgap of AlGaAs. The signal beam wavelength should lie outside the exciton resonance to provide suitable small absorption, but in the range of sufficient electrorefraction. Thus the wavelength of the guided mode has to be a compromise between relatively low absorption and possibly high electrorefraction. The length of the sample is about a few millimetres so the value of absorption coefficient should be less than 1 cm^{-1}. The signal wave confined in waveguide attains large intensity (of the order of 1000 W/cm^2) and erases the grating due to photoionization of the deep defects. Therefore a permanent illumination of the external waves is necessary to maintain the grating.

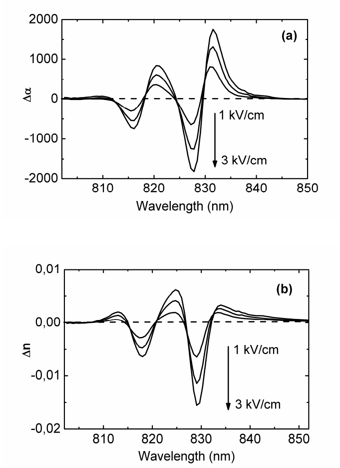

Fig. 5. (a) Differential electro-absorption spectrum, $\Delta\alpha = \alpha(E) - \alpha(0)$, for three values of the applied field intensity (measured by ITME). (b) The dependence of the refractive index changes on the wavelength obtained from Kramers-Krönig relation

Fig. 5. (a) Widmo elektro-absorpcji, $\Delta\alpha = \alpha(E) - \alpha(0)$, dla trzech wartości przyłożonego pola elektrycznego (zmierzone w ITME). (b) Zależność zmian współczynnika załamania od długości fali otrzymana z relacji Kramers'a-Krönig'a

4. Optical properties

The structure of samples was designed to form a single-mode waveguide for the wavelength range of a signal beam. The profile of refractive index of the sample and calculated transverse field intensity distribution of the fundamental TE_0 mode is presented in Fig. 6.

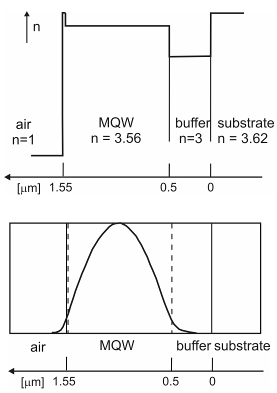

Fig. 6. Refractive index profile and transverse field distribution of TE_0 mode in the waveguide of the second type

Rys. 6. Rozkład współczynnika załamania i rozkład poprzeczny natężenia pola modu TE_0 w światłowodzie drugiego typu

5. Experimental setup

The experimental setup used in investigation of PR-MQW planar waveguides is presented in Fig. 7.

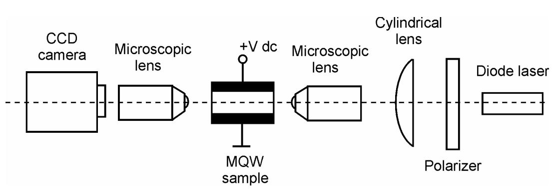

Fig. 7. The experimental setup used in investigation of the PR-MQW planar waveguides

Rys. 7. Układ doświadczalny do badania falowodów planarnych z rdzeniem PR-MQW

The laser beam is shaped by a cylindrical lens and by means of a microscopic lens focused on the end face of a waveguide. An output light after passing through a second microscopic lens is observed by the CCD camera. The setup allows to study the photorefractive effect in planar waveguide by monitoring the output beam intensity distribution.

Light beam at near-resonant wavelength has been coupled into the waveguide. Its cross section at the output plane of the waveguide is shown in Fig. 8. Obtained results are in our opinion encouraging for further experiments including the influence of photorefractive grating on propagation.

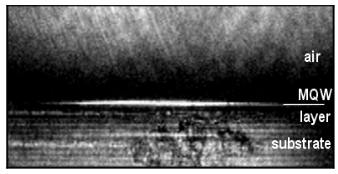

Fig. 8. The image showing a light beam in output plane of the waveguide

Rys. 8. Obraz przedstawiający wiązkę świetlną w płaszczyźnie wyjściowej falowodu

6. Summary

Photorefractive multiple quantum wells are typically used as thin holographic films operating in transmission geometry. Basing on the results of electro-absorption and electro-refraction of MQW samples we proposed a conception of employing of a PR-MQW structure in Franz-Keldysh geometry as a guiding layer of a planar waveguide. Preliminary experimental results show that light at theoretically predicted wavelength can propagate through MQW waveguide.

In this case the external laser beams writing the photorefractive grating in MQW material permit to control a propagating signal beam.

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