Excitonic polaritons in quantum-well structures under Bragg-reflection conditions

D. R. Yakovlev, G. R. Pozina, and V. P. Kochereshko
Physicotechnical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia
A. Waag, W. Ossau, and G. Landwehr
Physikalisches Institut der Universität Würzburg, 97074 Würzburg, Germany

(Submitted 7 March 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **61**, No. 7, 613–616 (10 April 1995)

Reflection of light in the region of excitonic resonances has been studied in periodic CdTe/(Cd,Mg)Te heterostructures with quantum wells. There is a huge increase in the optical reflection coefficient in crystals which satisfy the Bragg conditions $kd=\pi$ (where k is the wave vector of the light, and d is the period of the structure). © *1995 American Institute of Physics.*

Measuring the optical reflection spectra of semiconductor structures with quantum wells and superlattices is a promising method for studying and characterizing the properties of semiconductor quantum-well heterostructures. Analysis of the excitonic reflection line makes it possible to study the longitudinal–transverse splitting of an excitonic polariton as a function of the parameters of the heterostructure and external magnetic and electric fields. Studies by this method have demonstrated that there is a transition from a quasi-2D to a quasi-3D carrier motion as the period is reduced in short-period GaAs/(Al, Ga)As superlattices.[1] It has been observed[2] that an external magnetic field can induce a transition to a state of a spin superlattice in semimagnetic CdTe/(Cd, Mn)Te heterostructures. A huge increase in the oscillator strength of an exciton in quantum wires has been observed.[3]

Previous analysis of the reflection spectra of periodic quantum-well semiconductor structures has been restricted to the case $kd\ll 1$, i.e., the case of short-period structures, for which one can use the approximation of an effective dielectric medium for a description.[4] In this letter we are reporting the use of resonant excitonic reflection of light to study structures with quantum wells separated by barriers with thicknesses comparable to the wavelength of the light in the medium. In this case the effective-medium approximation clearly must be abandoned. A theoretical analysis of this case by Ivchenko *et al.*[5] predicts a huge increase in the optical reflection coefficient for light near an excitonic resonance in a semiconductor quantum well whose period satisfies the Bragg condition for the propagating light wave: $kd=\pi$ (where $k=\omega n/c$ is the wave vector of the light, d is the period of the structure, and n is the refractive index for light in the medium).

In the present experiments we used semiconductor heterostructures with a periodic array of ten CdTe/$Cd_{0.6}Mg_{0.4}Te$ quantum wells, grown by molecular beam epitaxy on $Cd_{0.96}Zn_{0.04}Te$ substrates in the (100) orientation. The widths of the quantum wells in the structures were $L_z=70-75$ Å . The period of the structure was varied from 100 to 2000

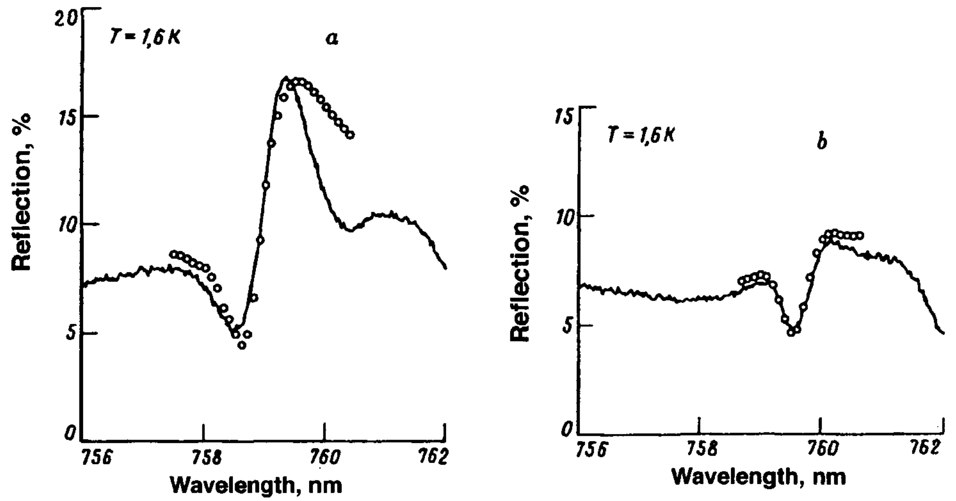

FIG. 1. Reflection spectra for the case in which light is incident obliquely ($\varphi=45°$) on a "Bragg" CdTe/CD$_{0.6}$Mg$_{0.4}$Te quantum-well structure with a period $d=1620$ Å (a) and for an "anti-Bragg" quantum-well structure with a period $d=850$ Å (b). $L_z=75$ Å, $T=1.6$ K. The points are the results of calculations with the following parameter values: a) $\omega_0^{-1}=759.1$ nm, $\hbar\Gamma=0.85$ meV, $\hbar\Gamma_0=0.12$ meV, $l=860$ Å. b) $\omega_0^{-1}=759.6$ nm, $\hbar\Gamma=0.75$ meV, $\hbar\Gamma_0=0.14$ meV, $l=300$ Å. The refractive index for Cd$_{0.6}$Mg$_{0.4}$Te, $n=2.64$, was taken from Ref. 8.

Å. It was determined from the growth rate and monitored by x-ray diffraction. The structures were not deliberately doped; the residual impurity concentration was $\sim 10^{16}$ cm^{-3}

If a high reflection coefficient is to be achieved for a quantum-well structure, it is necessary to satisfy the Bragg condition within 10%. This condition must hold for the projection of the light wave vector onto the axis of the structure (k_z): $k_z d=\pi$, where $k_z=\frac{\omega}{c}\sqrt{n^2-\sin^2\varphi}$, and φ is the angle of incidence of the light. By choosing the appropriate angle of incidence, one can thus satisfy the Bragg condition more accurately for the z component of the wave vector of the light.

Figure 1 shows reflection spectra in the region of a heavy-exciton resonance for two CdTe/Cd$_{0.6}$Mg$_{0.4}$Te quantum-well structures. The spectra were recorded as p-polarized light was incident obliquely ($\varphi=45°$) on the structure at $T=1.6$ K (Ref. 1). Figure 1a shows a spectrum of a "Bragg" quantum-well structure with a period $d=1620$ Å, which made it possible to nearly satisfy the Bragg condition $k_z d=1.09\pi$. Figure 1b shows the reflection spectrum of an "anti-Bragg" structure ($kd=\pi/2$) with $d=850$ Å and $k_z d=0.57\pi$. The spectra of both structures clearly reveal a resonance line of an excitonic reflection. Comparison of the spectra of these structures shows that both the amplitude and the width of the excitonic-reflection line are much greater in the "Bragg" quantum-well structure than in the "anti-Bragg" one.

As was shown in Ref. 5, light waves reflected from each well in a "Bragg" quantum-well structure are summed at the outer surface of the structure in the same phase, which is a multiple of 2π. The optical reflection coefficient of such a structure is the "sum" of the reflection coefficients of each of the individual quantum wells. For the "anti-Bragg" structure, in contrast, the waves reflected from the individual quantum wells are summed out of phase at the surface, so the resultant reflection coefficient is reduced.

It was shown in Ref. 4 that the amplitude reflection coefficient of a single quantum well is given by

$$r_1=\frac{i\Gamma_0}{\omega_0-\omega-i(\Gamma_0+\Gamma)}, \tag{1}$$

where Γ_0 is the radiative damping of an exciton, Γ is the nonradiative damping, and ω_0 is the resonance frequency of the exciton. In quantum-well structures which satisfy the Bragg conditions, the amplitude reflection coefficient is

$$r_N=\frac{iN\Gamma_0}{\omega_0-\omega-i(N\Gamma_0+\Gamma)}, \tag{2}$$

where N is the number of quantum wells.[5] In a "Bragg" quantum-well structure there is accordingly a pronounced increase in the optical reflection coefficient in the vicinity of an excitonic resonance, due to an N-fold increase in the radiative damping of an exciton. The amplitude of the excitonic-reflection line should therefore increase with increasing number of quantum wells, in proportion to $N\Gamma_0/(\Gamma+N\Gamma_0)$. In the limit $N\rightarrow\infty$, the optical reflection coefficient of a "Bragg" quantum-well structure should have the behavior $r_N\rightarrow 1$. The half-width (γ) of the excitonic-reflection line in a "Bragg" structure is calculated as $\gamma=\Gamma+(1+(n-1)/n+1)N\Gamma_0$. It is greater than the width of the line for an anti-Bragg structure under the condition $N\Gamma_0\geqslant\Gamma$. As is shown below, the latter condition is satisfied well in the quantum-well structures studied.

We have experimentally verified (Fig. 1) the theoretical prediction that the amplitude and width of the excitonic-reflection line increase in "Bragg" heterostructures. For a detailed quantitative description of the effect, we analyzed reflection spectra on the basis of the equations of Ref. 5. The results of this analysis are shown by the points in Fig. 1. The parameter values used in the calculations are given in the figure caption. Both spectra can be described well, with sets of parameters which are approximately the same ($\hbar\Gamma=0.85$ meV and $\hbar\Gamma_0=0.12$ meV for the "Bragg" quantum-well structure and $\hbar\Gamma=0.75$ meV and $\hbar\Gamma_0=0.14$ meV for the "anti-Bragg" structure). These results indicate that the theory gives a successful description of the experimental spectra.

Yet another manifestation of a coherent interaction of light with a periodic heterostructure, which can be observed in quantum-well structures with barrier thicknesses close to the "Bragg" values, arises from an interference of light waves which are reflected from each of the quantum wells and which arrive at the surface of the structure with a phase which is not exactly a multiple of 2π. In the reflection spectra of such structures we can see some very narrow interference features against the fairly broad excitonic-reflection line (see Fig. 3 in Ref. 5). Figure 2 shows a reflection spectrum for normal incidence of light ($\varphi=0$) for a periodic structure with ten CdTe/$Cd_{0.58}Mg_{0.42}Te$ quantum wells with a period $d=1585$ Å ($kd=1.11\pi$) in the region of a heavy exciton in the quantum well. Note the narrow peak in the spectrum at 752 nm. This peak, which

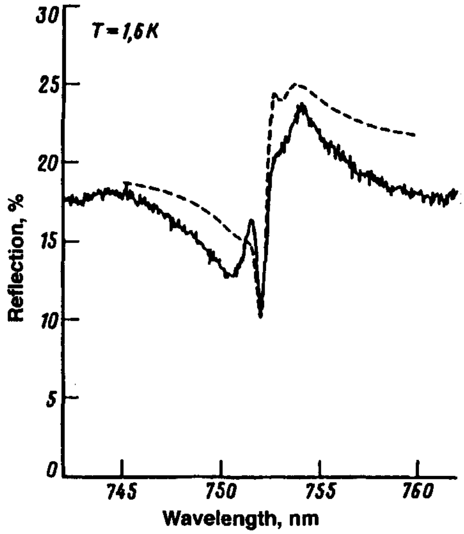

FIG. 2. Reflection spectrum for the case in which light is incident normally ($\varphi=0°$) on a periodic CdTe/Cd$_{0.58}$Mg$_{0.42}$Te quantum-well structure. The structure is approximately a "Bragg" structure with a period $d=1585$ Å ($kd=1.11\pi$) and $L_z=70$ Å. Dashed curve—Theoretical with the parameter values $\omega_0^{-1}=752.4$ nm, $\hbar\Gamma=0.8$ meV, $\hbar\Gamma_0=0.17$ meV, $l=830$ Å, and $n=2.64$.

lies against the background of the broader excitonic-reflection line, is clearly of interference origin. An analysis of this spectrum with the parameter values $\hbar\Gamma=0.8$ meV and $\hbar\Gamma_0=0.17$ meV is shown by the dashed curve in Fig. 2.

In summary, we have carried out the first study of the spectra of resonant excitonic reflection of light in periodic structures with quantum wells which satisfy the Bragg conditions. It has been found that the optical reflection coefficient of such structures increases dramatically because of a constructive interference of light at the surface of the sample reflected from each of the quantum wells in the structure. The effect studied here may be of interest for the development of selective narrow-band mirrors in semiconductor microcavity heterostructure lasers.[6,7]

We wish to thank E. L. Ivchenko, A. I. Nesvizhskiĭ, and S. Jorda for a discussion of the results. We also thank the Volkswagen Foundation for support of this study.

[1] E. L. Ivchenko, V. P. Kochereshko, P. S. Kopev *et al.*, Solid State Commun. **70**, 529 (1989).
[2] E. L. Ivchenko, A. V. Kavokin, V. P. Kochereshko *et al.*, Phys. Rev. B **46**, 7713 (1992).
[3] E. L. Ivchenko, A. V. Kavokin, V. P. Kochereshko *et al.*, Superlattices and Microstructures **12**, 317 (1992).
[4] E. L. Ivchenko, Fiz. Tverd. Tela (Leningrad) **33**, 2388 (1991) [Sov. Phys. Solid State **33**, 1344 (1991)].
[5] E. L. Ivchenko, A. I. Nesvizhskiĭ, and S. Iorda, Fiz. Tverd. Tela (Leningrad) **36**, 2118 (1994) [Semiconductors **36** 1156 (1994)].
[6] G. Björk, S. Mashida, Y. Yamamoto, and K. Igeta, Phys. Rev. B **44**, 669 (1991).
[7] V. Savona, L. C. Andreani, P. Schwendimann, and A. Quattropani, Solid State Commun. **93**, 733 (1995).
[8] H. J. Lugauer, F. Fischer, T. Litz *et al.*, Semicond. Sci. Technol. **9**, 1567 (1994).

Translated by D. Parsons