Magnetic trapping of charge carriers in the quantum wells of an asymmetric two-well semiconductor structure

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It was found that in a magnetic field applied parallel to the layers of a quantum-size structure a luminescence line associated with the second quantum-well subband of a two-well system is excited. This effect is due to the magnetic localization of charge carriers in quantum wells which is accompanied by a weakening of the tunneling coupling between the wells. The results for a structure with strong tunneling coupling between the wells are described satisfactorily by a simple semi-quantitative model with parabolic wells. A nonmonotonic magnetic-field dependence of the intensities of the luminescence lines was observed for a sample with weakly coupled wells. © *1995 American Institute of Physics.*

In the last few years there has been considerable interest in investigations of the effect of a magnetic field applied parallel to the layers (see, for example, Refs. 1–4), which has not been studied as extensively as the effect of a perpendicular field, on the electronic states and other properties of charge carriers in semiconductor heterostructures. The attention given to this problem stems, in particular, from fact that a parallel magnetic field can drastically affect tunneling processes in complicated heterosystems because in such a field the extent of the wave functions in a direction perpendicular to the layers changes and resonance crossings of the dispersion curves corresponding to neighboring wells in the structure appear.[5–7]

We have observed directly the magnetic localization of charge carriers in square quantum wells (QW) of an asymmetric two-well structure in a magnetic field oriented parallel to the layers of the structure. We found that in a magnetic field there is a redistribution of the intensities of the luminescence lines corresponding to the recombination radiation of each of the quantum wells. This indicates that the tunneling probability between the quantum wells decreases as the intensity of the magnetic field increases.

The main experiments were performed on two GaAs/Al$_x$Ga$_{1-x}$As structures ($x \simeq 0.3$), grown on a TSNA-25 molecular-beam epitaxy apparatus at the Technological Center of the Physics Institute of the Academy of Sciences. Each structure contained a pair of quantum wells with the nominal widths $d_1 = 300$ Å and $d_2 = 200$ Å . The structures differed by the degree of coupling between the quantum wells, as determined by the

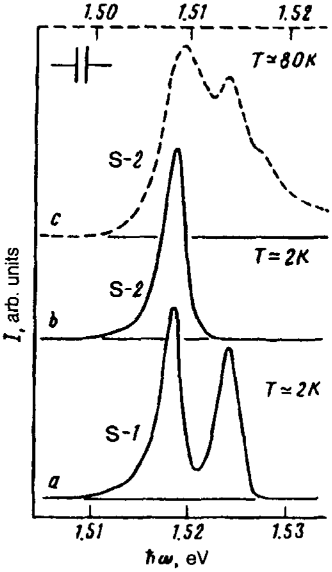

FIG. 1. Luminescence spectra of structures with weakly (a) and strongly (b,c) coupled quantum wells at temperatures ≃2 K (a,b) and ≃80 K (c). For convenience in comparing the spectra the energy scale $\hbar\omega$ in c (dashed line at the top) is shifted with respect to the scale in a and b (solid line at the bottom) by the amount of the temperature change in the width of the band gap.

width of the barrier separating the wells. The structure S-1 with weakly coupled (almost isolated) quantum wells had a barrier of width $b = 120$ Å , while the other structure (S-2) with strongly coupled quantum wells had a barrier with a width of $b = 20$ Å .

The samples were excited in a quasistationary manner (the interruption frequency was 1000 Hz) with a 0.63-μm radiation from a 20-mW He–Ne laser. The laser beam was focused into a spot with a diameter of about 0.5 mm on the surface of the structure. The recombination radiation was collected from the excited surface of the sample. The luminescence was analyzed with a MDR-2 monochromator with a 600 lines/mm grating and recorded with a photomultiplier. The samples were placed in superfluid helium at the temperature $T \simeq 2$ K. A magnetic field with an intensity of up to 55 kOe was produced by a superconducting solenoid.

The photoluminescence spectra of the experimental structures without a magnetic field ($H = 0$) are shown in Fig. 1. Two lines can be seen in the spectrum of the structure with almost isolated wells. The low-frequency line corresponds to luminescence from the wide well and the other line corresponds to luminescence from the narrow well2) (Fig. 1a). At liquid-helium temperatures the relative intensity of the observed emission lines is determined by the ratio of the tunneling time of the charge carriers between the wells and the recombination time. For the S-1 structure the tunneling time is much longer than the recombination time, so that both lines have approximately the same intensity.3) For the S-2 structure the ratio of the times is reversed, and there is enough time for a large fraction of the nonequilibrium charge carriers trapped in the narrow quantum well to

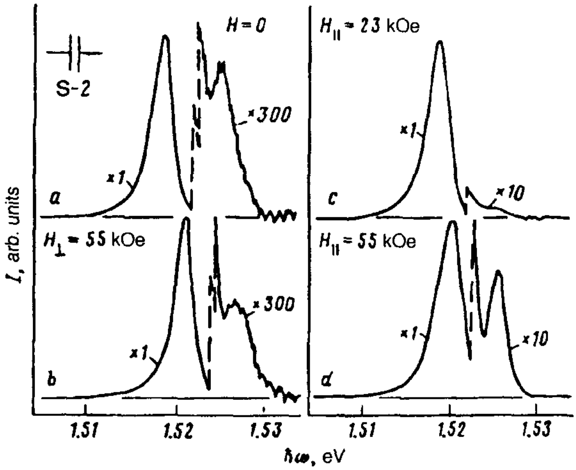

FIG. 2. Emission spectra of a structure (S-2) with weakly coupled quantum wells in the absence of a field (a), in a parallel magnetic field with intensity $H_\parallel = 23$ kOe (c) and $H_\parallel = 55$ kOe (d), and in a perpendicular field with $H_\perp = 55$ kOe (b).

tunnel into the wide quantum well (where their energy is lower) before recombining. For this reason, at $T \simeq 2$ K the emission line from the narrow well is nearly invisible in the luminescence spectrum of this structure (Fig. 1b): It is 100 times weaker than the line from the wide well (Fig. 2a). At liquid-nitrogen temperatures the thermally activated tunneling from the wide well into the narrow well fills the lower energy level in the narrow well, and the intensity of the short-wavelength line is found to be comparable to that of the emission line from the wide well (Fig. 1c).

The luminescence spectra of the S-2 structure in a magnetic field are shown in Fig. 2. We see that in a magnetic field oriented parallel to the layers of the structure an emission line associated with the narrow well is excited (Figs. 2c and 2d). The intensity of this line increases substantially as the intensity of the field increases, and in the maximum field it reaches a magnitude approximately 30 times greater than the intensity of this line in the absence of a field (compare Figs. 2a and 2d). At the same time, a magnetic field oriented perpendicular to the layers of the structure does not greatly affect the intensity of the emission line from the narrow well (Fig. 2b). In each case a diamagnetic shift of the luminescence line of the wide well is visible.

A magnetic field applied parallel to the layers also gives rise to appreciable redistribution of the line intensities in the spectrum of the S-1 structure: In the maximum field each emission line has approximately the same intensity.

Data on the change in the intensities of the luminescence lines of the experimental structures with increasing field intensity are shown in Fig. 3. For the structure with strongly coupled quantum wells the increase in the ratio I_2/I_1 of the intensities I_2 and I_1 of the emission lines of the narrow and wide quantum wells, respectively, with increasing field intensity, which indicates that the relative number of nonequilibrium charge carriers in the narrow quantum well increases, is continuous (Fig. 3a), while for the

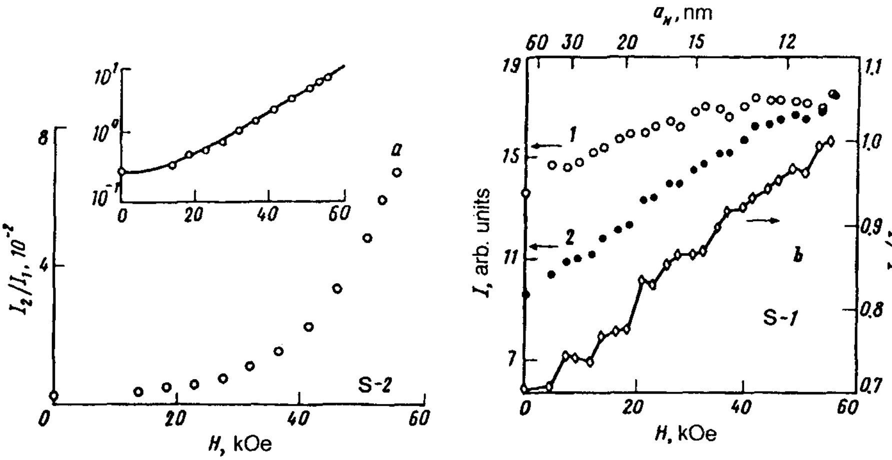

FIG. 3. a) Ratio of the emission line intensities I_2 and I_1 of the narrow and wide quantum wells, respectively, as a function of the magnetic field intensity for the structure S-2. Inset: Analysis of the experimental data according to Eq. (2); solid line—computational results. b) I_1 and I_2 (scale on the left) and the ratio I_2/I_1 (scale on the right; for convenience, the experimental points are connected by rectilinear segments) as a function of H for the structure S-1.

structure with almost isolated quantum wells this dependence has a stepped form: The sections with a small change in the ratio I_2/I_1 are replaced by a sharp increase in the value of this ratio for some values of the field strength; the absolute value of the intensity I_2 as a function of H also has a stepped character (Fig. 3b).

The features of the redistribution of nonequilibrium charge carriers between quantum wells in a magnetic field, which are common to both structures, can be clearly explained qualitatively. It is obvious that the observed distribution of the charge carriers is associated with the change occurring in the probability of tunneling through the potential barrier that separates the potential wells in a magnetic field. This probability is determined by the overlapping of the wave functions of the charge carriers in the narrow and wide wells. A magnetic field applied parallel to the layers of the structure compresses the wave functions in a direction perpendicular to the walls of the quantum wells and intensifies carrier localization in the corresponding wells. As a result, the overlapping of the wave functions, and hence, the probability of tunneling decrease with increasing field intensity.4) In other words, the rate of relaxation from the first excited state of an asymmetric system of coupled quantum wells, which is mainly localized in the narrow well, into the ground state localized in the wide well decreases. The population of the first excited level, and hence the number of particles in the narrow well therefore increase as the intensity of the field increases.

Magnetic localization of a wave function becomes appreciable when the magnetic length $a_H=(\hbar c/eH)^{1/2}$ approaches, as the field intensity increases, one-half the width of the quantum well. For 300-Å and 200-Å wells this occurs in a field with H of about 30 and 65 kOe, respectively.

We note that in a similar structure containing a pair of quantum wells of width 120

Å and 160 Å separated by a barrier of width $b=20$ Å, the excitation of a luminescence line associated with the narrow well was not observed even in the maximum experimental fields $H \simeq 55$ kOe achievable in our experiments. In accordance with what we have said above, the intensity of the short-wavelength emission line for this pair of wells should start to increase rapidly in a field of intensity greater than 100 kOe.

A simplified quantitative analysis of the results obtained can be made on the basis of a model in which square quantum wells are replaced by parabolic wells. The problem of a parabolic quantum well in a parallel magnetic field can be solved analytically. In this problem the wave function of the ground state is

$$\varphi(z)=\frac{1}{\pi^{1/4}\sqrt{a(H)}}\exp\left(-\frac{z^2}{2a^2(H)}\right) \tag{1}$$

(the z axis is oriented perpendicular to the walls of the well), where $a(H)=a_0a_H/(a_0^4+a_H^4)^{1/4}$, and $2a_0$ is the $1/e$ width of the probability distribution in the parabolic well in the absence of a field. Assuming that the ground states of the narrow and wide quantum wells are described by the functions (1) with the corresponding parameters a_{01} and a_{02} and the maxima of the wave functions are split from one another by an amount L equal to the distance between the centers of the wells, it is easy to calculate the overlap integral of the wave functions and then to find the tunneling time between these states, which is inversely proportional to the square of this integral. As a result, we obtain for the tunneling time

$$\tau_{\text{tun}} \propto \exp\left(-\frac{L^2}{a_1^2(H)+a_2^2(H)}\right). \tag{2}$$

In the experimental range of field intensities the preexponential factor for our structures is virtually independent of H and is therefore dropped.

For a structure with strongly coupled quantum wells (S-2) the intensities of the luminescence lines of the narrow and wide wells satisfy the inequality $I_2/I_1 \ll 1$. As noted above, this means that τ_{tun} is much shorter than the lifetime of the nonequilibrium charge carriers. In this case it can be assumed that $I_2/I_1 \propto \tau_{\text{tun}}$. Equation (2) agrees well with the experimental data (the inset in Fig. 3a) for the following values of the parameters: $L=350$ Å, $a_{01}=170$ Å, and $a_{02}=115$ Å. We note that despite the very approximate character of the model employed, the distance L between the centers of the wells is found to be not much different from the actual value $L=b+(d_1+d_2)/2=270$ Å, and the quantities $2a_{01}$ and $2a_{02}$ are close to the well widths d_1 and d_2, respectively.

For the S-2 structure τ_{tun} is comparable to the lifetime. This value is estimated from the experimental data with a large uncertainty, especially for large H when $I_1 \simeq I_2$. For this reason, we did not use Eq. (2) to analyze these data. However, the explanation of the stepped character of the H dependences of I_2 and I_2/I_1 is very difficult to explain. At present, we cannot give a satisfactory interpretation of this fact. We note, however, that the features observed in these curves arise when the magnetic length a_H is close to one of the characteristic dimensions of the experimental two-well system (d_1, d_2, $d_1/2$, etc.). We also note that the above-mentioned resonance crossing of the dispersion curves of the lower electronic subbands of the neighboring quantum wells of the present structure could be manifested in the luminescence in a field with $H \simeq 17$ kOe ($a_H \simeq 200$ Å).

In summary, we have discovered that magnetic localization of nonequilibrium charge carriers in quantum wells brings about a redistribution of the intensities of the luminescence lines of an asymmetric system of two coupled quantum wells. This shows that a magnetic field applied parallel to the layers of the structure can influence the tunneling rate of the charge carriers. In addition, experiments with almost isolated wells showed that the weak interaction between them is very sensitive to a parallel magnetic field. Such a field can therefore be used effectively to investigate this interaction.

In conclusion, we note that the luminescence lines which we investigated are of an excitonic nature. In our discussion, which was mainly qualitative, we did not fully account for this circumstance, and we assumed essentially that the redistribution of nonequilibrium charge carriers between the quantum wells occurs before the carries are bound into excitons. For the reverse ratio of the relaxation rates and binding the phenomenon is much more difficult to analyze, but the experimentally observed overall picture apparently remains the same.

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2)When we say that an emission line is associated with one of the wells, we have in mind the fact that the wave functions of the recombining particles are localized mainly in the given well, as happens in an asymmetric system of coupled quantum wells, although the corresponding energy levels belong to the entire system as a whole.

3)The fact that the intensities of these lines are different can be attributed, in addition to the tunneling between the quantum wells, to the difference in the rates of trapping of charge carriers in the narrow and wide wells (subbarrier excitation was used in the experiments described above), to the lifetimes in the wells, and to other factors.

4)The overlapping of the wave functions also changes as a result of the displacement of the centers of the cyclotron orbits, which occurs when the intensity of the field changes. This effect is probably less important in our case, as is confirmed by the computational results presented below.

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