Excitons in GaAs/AlAs superlattices near a type-II–type-I transition

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A type-II–type-I transition in GaAs/AlAs superlattices has been studied by optical magnetic-resonance detection and level-anticrossing spectroscopy. Three types of excitons, differing in exchange interactions and lifetimes, were detected near the transition. The exchange splitting of exciton levels in type-I superlattices was measured. The detection of a nonresonant effect of a microwave field on the luminescence of GaAs/AlAs superlattices made it possible to determine the complex structure of the emission line.

The fine structure of exciton levels in GaAs/AlAs superlattices of type II, in which an exciton is formed from a hole in a GaAs layer (Γ is the maximum of the valence band) and an electron in an AlAs layer (X is the minimum of the conduction band), has been studied previously by optical magnetic-resonance detection,[1–4] a quantum-beat method,[5,6] and a polarized-luminescence method.[7] There is considerable research interest in the g-factors and exchange interactions of excitons in type-I superlattices, in which the Γ electron and the Γ hole are localized in one GaAs layer, and also in the type–II–type–I transition, in the course of which the relation between the energies of the X electron in AlAs and the Γ electron in GaAs changes. In this letter we are reporting the first results of a study of optical magnetic-resonance detection and the anticrossing of exciton levels in a GaAs/AlAs superlattice near the type–II–type-I transition. The structure of the emission line of the GaAs/AlAs superlattice was studied by detecting the nonresonant effect of a microwave field on the luminescence.

The optical magnetic-resonance detection (OMRD) at a frequency of 35 GHz and an anticrossing of exciton levels were detected at temperatures of 1.6–4.2 K from the circular polarization of the luminescence excited by the unfocused light from an argon laser (488 or 514.5 nm, 0.5–10 mW). This luminescence was detected along the direction of the static magnetic field by means of the OMRD spectrometer described in Ref. 8. The GaAs/AlAs superlattices were grown by molecular beam epitaxy. Sample E913 had a length of 23.4 mm and a gradient of the GaAs/AlAs composition in the plane of the lattice: from 20.8/12.2 Å at $x=0$ to 22.8/11.2 Å at $x=23.4$ mm. Optical measurements revealed a transition from a type-II superlattice to a type-I superlattice in this sample in the region $x=13$–20 mm.[6] This sample could be moved vertically in such a way that the luminescence would be excited and measured selectively in a certain region of the sample. We also studied type-II superlattices as described in Refs. 4 and 5.

Figure 1 shows the circular polarization of the luminescence versus the magnetic

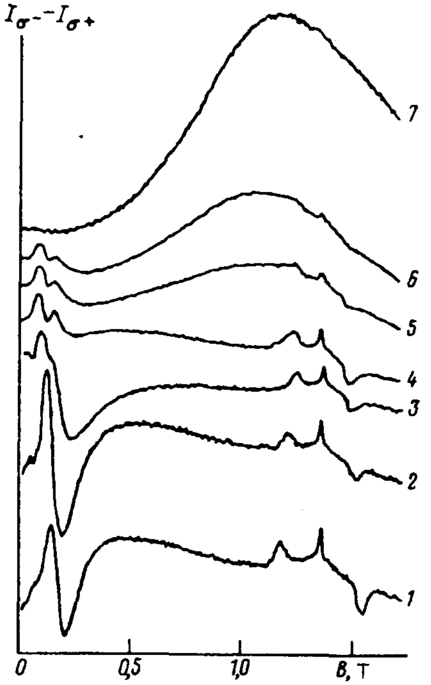

FIG. 1. Circular polarization of the luminescence versus the magnetic field in a GaAs/AlAs superlattice with a composition gradient in the plane of the lattice (sample E913) as the exciting beam was moved over the sample in steps from the type-II region into the type-I region. *1*–$x=0$; *2*—8 mm; *3*—12; *4*—16; *5*—17.5; *6*—19; *7*—21 mm. $T=1.6$ K, $B\|$ [001], $\nu=35$ GHz, $P=500$ mW.

field at various regions in sample E913 as the exciting beam was moved in steps from the type-II region (1) to the type-I region (7). In these spectra we see the OMRD lines of free electrons and pairs of exciton lines (curves *1–6*, $B=1.1$–1.6T) which are typical of type-II superlattices.[1–4] We also see some anticrossing signals at $B=0$–0.3 T which are independent of the microwave field. The OMRD line of electrons with the *g*-factor characteristic of a type-II superlattice (about 1.9) is observed all the way to the region corresponding to the type-I superlattice.

The OMRD and exciton anticrossing can be described by the spin Hamiltonian

$$\hat{H}=\beta\mathbf{B}\hat{g}_e\mathbf{S}_e+\beta\mathbf{B}\hat{g}_h\mathbf{S}_h+S_h\hat{c}S_e, \tag{1}$$

where the first two terms are the energies of the Zeeman interaction of an electron and a hole in the magnetic field **B**; the last term is their exchange interaction, characterized by the tensor $\hat{c}$; β is the Bohr magneton; $\mathbf{S}_e=1/2$; and $\mathbf{S}_h=1/2$ is the effective *g*-factor of a hole. Because of the low symmetry of the superlattice, the hole levels $J=\pm3/2$ and $J=\pm1/2$ are split by more than 10 meV. At 1.6 K, only the $J=\pm3/2$ is populated.

As we go from the type-II superlattice to the type-I one we see a decrease in the intensity of the OMRD signals and of the low-field anticrossing signals (curves 3–6 in Fig. 1). Near the II–I transition there is a change in the shape of the anticrossing (curves *2–6*). As we move toward the type-I region, the magnetic-field dependence of the circular polarization of the luminescence acquires some broad signals in high magnetic fields (curves *5–7*).

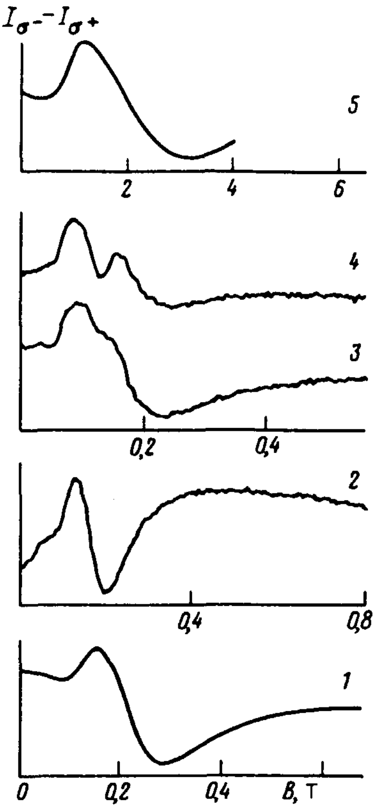

FIG. 2. Signals representing an anticrossing of exciton levels in samples E219 (curve 1) and E913 in the type-II region (curve *2*), in the regions approaching the II–I transition (curves *3* and *4*), and in the region of the type-I superlattice (curve *5*). The magnetic-field scale has been normalized to the magnitude of the exchange splitting c_z. $T=1.6$ K, $B\|$ [001].

Figure 2 shows exciton anticrossing signals in sample E219 (18/12 Å)—a superlattice near the II–I transition—and also in a region of sample E913 corresponding to the type-II superlattice (curve *2*) and various other regions progressively closer to the transition region (curves *3* and *4*). The magnetic-field scale for each spectrum is inversely proportional to the constant of the isotropic exchange splitting of excitons, c_z, found from the corresponding OMRD spectra. Also shown is the anticrossing in a region of a type-I superlattice (curve *5*).

For sample E219 the magnitude of the isotropic exchange splitting, $c_z/2$, of the "type-II excitons," found from the OMRD spectra, is 17 μ eV. For sample E913 we have $c_z/2=20$ μ eV at $x=0$ and 14 μeV at $x=16$ mm. These results agree with measurements of the splitting between the radiation exciton levels, $(c_x+c_y)/2$, found by quantum-beat methods in these samples (9.3 μeV for E219 and 6.5 μeV for the region $x=15.5$ mm in sample E913).[6]

The anticrossing signals in the type-II superlattice far from and close to the II–I transition are quite different, as can be seen by comparing spectra *1* and *2* in Fig. 2. The spectra were recorded in samples E219 and E913 ($x=0$), which had approximately equal values of c_z. In the II–I transition region of sample E913 we see an additional splitting of the anticrossing signals. It follows from the optical measure-

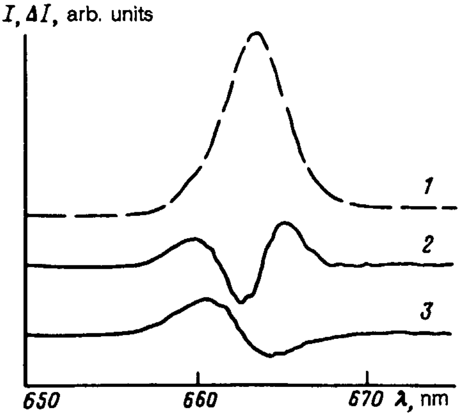

FIG. 3. 1: Luminescence spectrum. 2, 3: Spectra of the signal corresponding to the nonresonant effect of the microwave field on the intensity of the σ^- luminescence component in a GaAs/AlAs superlattice of type II (17.4/26 Å). The intensity of the exciting light was (2) 10 or (3) 0.5 mW. $B=1$ T, $\nu=35$ GHz, $P=500$ mW, $f=280$ Hz, $T=1.6$ K.

ments that the radiative lifetime τ changes from 20 to 0.3 ns in the transition region of sample E913 ($x=14$–19 mm); for sample E219 we have $\tau=10$ ns. Observation of the OMRD requires a longer radiative lifetime (usually more than 100 ns). In the type-II superlattices studied in Refs. 4 and 5, this time was 1–10 μs. The limitations arise from the condition $\gamma H_1 \geqslant \tau$, where γ is the gyromagnetic ratio for an electron, and H_1 is the amplitude of the microwave field at the sample. There are no such restrictions for the detection of anticrossing signals. It can be seen from Figs. 1 and 2 that structural features appear in the anticrossing spectra near the II–I transition. These features can be explained by a coexistence of "type-II excitons" and the "II–I excitons," with a large exchange splitting and a shorter lifetime, which are characteristic of the transition region. We do not observe OMRD signals from the II–I excitons, apparently because of a short lifetime.

The shape of the broad signals on the field dependence of the circular polarization of the luminescence in the type-I superlattice is similar to the shape of the anticrossing signals in a type-II superlattice. We also observed signals of this sort in other type-I superlattices. It might be suggested that they belong to an anticrossing of "type-I" excitons with a far greater exchange splitting, and one might attempt to evaluate this splitting. Here we should note that a type-I superlattice does not have an exchange splitting between the two radiating exciton levels, and there is a substantial change in the electron g-factor g_e. The hole g-factor, $g_h=2.6$, was determined in sample E913 from quantum-beat and optical-orientation experiments. The results agree well with the overall dependence of g_h on the thickness of the GaAs layer which was found in Ref. 5. Calculations using spin Hamiltonian (1) yield estimates of the exchange splitting ($c_z/2 \approx 150$ μeV) and the g-factor ($g_e \approx 0.9$), and they explain the observed orientation dependence of the anticrossing signals. The estimate of g_e found for a superlattice with a 21-Å well is in reasonable agreement with the results of Ref. 9.

In these experiments we made the first study of the effect of a microwave field on the luminescence of a GaAs/AlAs superlattice. Figure 3 shows the luminescence spectrum of a type-II superlattice (curve *1*), along with spectra of the signal corresponding to the change in the luminescence intensity upon modulation of the microwave power. These spectra were recorded at various levels of the optical excitation (curves *2* and *3*). Nonresonant background signals of this sort, which are usually observed in the OMRD of semiconductors and which stem from the electric component of the microwave field, have recently been used to study the nature of the luminescence and for optical detection of cyclotron resonance.[11,12] The fact that the microwave field has different effects on different parts of the superlattice emission line and the fact that the effects depends on the excitation intensity are evidence that the radiation is of a different nature. The decrease in the luminescence intensity caused by the microwave field is usually attributed to an impact ionization of bound excitons,[12] which results in an intensification of the emission of free excitons and a recombination involving free electrons. Further research is required to determine the correlation between the behavior found here and the spectra of OMRD and the magnetic circular polarization of the luminescence.

In summary, particular features of the behavior of the OMRD and the anticrossing have made it possible to observe three types of excitons, with parameter values characteristic of type-II and type-I superlattices and of a transition region. In the type-II superlattice, the electron and hole are localized in different layers, so the exciton has a longer lifetime (more than 1 μs) and a weak exchange interaction. In the II–I region, the energies of the bottom of the conduction band in the barrier (AlAs) and the well (GaAs) equalize. As a result, an electron may tunnel between barriers through the well. The lifetime decreases, and the exchange interaction strengthens, in the process. The localization of the electron and the hole in a common GaAs layer in a type-I superlattice leads to a short lifetime (less than 1 ns) and a far stronger exchange interaction (stronger by more than an order of magnitude). To the best of our knowledge, these have been the first measurements of the exchange interaction in a type-I superlattice.

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