# Magnetic resonance and anticrossing of levels of excitons trapped at opposite interfaces in type-II GaAs/AlAs superlattices

P. G. Baranov, I. V. Mashkov, and N. G. Romanov
*A. F. Ioffe Physicotechnical Institute, Russian Academy of Sciences,*
*194021 St. Petersburg, Russia*

C. Gourdon and P. Lavallard
*Groupe de Physique des Solids, Université Paris-7, Toour 23, 2 Place Jussieu,*
*F75251 Paris Cedex 05, France*

R. Planel
*Laboratoire des Microstructures et Microélectronique, 196, Avenue Henri Ravera,*
*F92225 Bagneu Cedex, France*

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Excitons trapped at different interfaces in type-II GaAs/AlAs superlattices have been studied selectively through optical detection of magnetic resonance. That excitons are trapped at opposite interfaces is proved unambiguously by measurements of an anticrossing of exciton levels based on the linear polarization of luminescence. Excitons characterized by exchange splittings corresponding to the trapping of an electron and a hole at points separated by a distance equal to the period of the superlattice have been detected. © *1994 American Institute of Physics.*

In type-II GaAs/AlAs superlattices, in which an exciton is formed by a hole in a GaAs layer (a Γ maximum of the valence band) and an electron in an AlAs layer (the $X$ minimum of the conduction band), recombination processes occur at the heterojunctions between layers (at the interfaces). These processes can be used to advantage to study the interfaces. Methods of optical detection of magnetic resonance (ODMR) in type-II GaAs/AlAs superlattices were developed in Refs. 1–4. The system of exciton energy levels was established unambiguously. It was shown[3,4] that the exchange splittings in an exciton are governed by the period of the superlattice, that they vary over the interval 0.5–50 $\mu$eV for superlattices with periods of 75–20 Å , and that they are essentially independent of the relation between the widths of the GaAs and AlAs layers within a period. A theoretical explanation of this effect was offered in Ref. 5. It has been shown[1] through studies by ODMR that the symmetry of the excitons in a type-II superlattice is lower than the symmetry of the superlattice itself ($D_{2d}$). In this case one observes a coexistence of two classes of excitons in a single superlattice. The two classes have approximately equal exchange splittings, while they have different $\langle 110\rangle$ $x$ and $y$ axes. A splitting of radiative levels of excitons not seen in type-I superlattices has been observed. The magnitude of this splitting, which has been studied not only by ODMR[3,4] but also by a quantum-beat method,[6,7] amounts to about 50% of the isotropic exchange splitting. It also depends on the period of the superlattice. In order to explain these results, it is necessary to note that the symmetry of an ideal heterojunction, $C_{2v}$, which is lower than the symmetry of the superlattice, completely lifts the degeneracy of the energy levels of trapped excitons. This circumstance can be demonstrated through direct diagonalization of the matrix of the complete Hamiltonian of an exciton, incorporating the energy levels of heavy and light holes. One should also note that the directions of the crystal bonds for the opposite interfaces make an angle of 90°.

The excitons are trapped at random irregularities of the interfaces. The exciton concentrations at the GaAs/AlAs and AlAs/GaAs interfaces are different. Previous efforts to selectively study excitons trapped at different interfaces have failed, because the exchange splittings have been approximately the same. In the present study, ODMR and level-anticrossing spectra were detected for excitons trapped at the opposite interfaces in short-period GaAs/AlAs superlattices. We also observed excitons characterized by exchange splittings which correspond to the trapping of an electron and a hole at points separated by a distance equal to the period of the superlattice.

Experiments were carried out on some specially designed and fabricated asymmetric superlattices in which the excitons would presumably be trapped at a single, definite interface. The superlattices were designed and fabricated in France; the experiments were carried out at the Ioffe Physicotechnical Institute. Two superlattices were fabricated. They differed only in the order of the GaAs and AlAs layers within a period, which consisted of four layers. The superlattices had the following structure: $n^+$ GaAs buffer layer, 1000 Å thick; superlattice of 336 periods; $n^+$ GaAs protective layer, 100 Å thick. Each period of superlattice $K$ 111 consisted of the following layers: 15 Å of GaAs, 12 Å of AlAs, 18 Å of GaAs, and 9 Å of AlAs. In superlattice $K$115, the layers were in a different order: 18 Å of GaAs, 12 Å of AlAs, 15 Å of GaAs, and 9 Å of AlAs.

Shown in the upper part of Fig. 1 is the structure of superlattice $K$115. Also shown here are wave functions calculated for an $X_z$ electron in an AlAs barrier and for a $\Gamma$ hole in a GaAs well. We see that both the electron and the hole are trapped in the widest layers of the superlattice. This circumstance is responsible for the trapping of the exciton at a definite interface, the "left" one (if we assume that the growth direction of the superlattice coincides with the $z$ axis). An exciton trapped at this interface is designated exc$L$1 in Fig. 1.

Shown in the lower part of Fig. 1 are ODMR spectra at a frequency of 35 GHz of superlattice $K$115, as found from the circular polarization of the luminescence, which was excited by the unfocused beam from an argon laser (488 nm) and which was detected along the direction of the static magnetic field. The ODMR spectrometer is described in Ref. 8. Spectra 1 and 2 correspond to laser power levels of 1 and 20 mW. In the spectra we see pairs of ODMR lines with opposite signs, which are typical of excitons in a type-II superlattice.[1–4] These lines result from transitions accompanied by electron spin flip. Between these pairs of lines there are also some narrow single lines, which correspond to unbound electrons. The widths of the signals and their behavior over the luminescence line are essentially the same as observed in type-II superlattices studied previously. The distance between the ODMR signals of excitons is proportional to the magnitude of the exchange interaction, $\Delta$. According to the dependence of $\Delta$ on the period of the superlattice reported in Refs. 3 and 4, the value found here, $\Delta = 23.8\ \mu$eV, corresponds to a period of 26 Å. This figure is smaller than the calculated local period for exc$L$1 in the

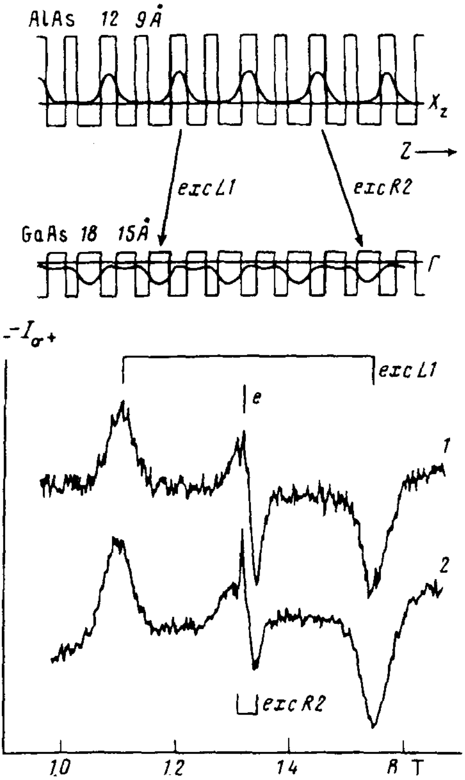

FIG. 1. Spectra of the optical detection of magnetic resonance at a frequency of 35 GHz, measured for sample $K115$ on the basis of the circular polarization of the luminescence. 1—The intensity of the exciting light is 1 mW; 2—20 mW. $T=1.6$ K, $B\|[001]$. Shown in the upper part of this figure is the structure of this superlattice, with the calculated wave functions for an $X_z$ electron and a Γ hole. Also shown here are recombination processes corresponding to the two types of excitons, exc$L1$ and exc$R2$. The $z$ axis coincides with the growth direction of the structure.

superlattice studied by an amount on the order of the thickness of one monolayer. Our conclusion regarding this difference between the periods of the theoretical and actual superlattices is also supported by an analysis of the Raman scattering spectra, according to which the local period is approximately the same, 27 Å .

An unexpected result is the observation, along with the ODMR signals of exc$L1$, of a second pair of exciton lines (exc$R2$ in Fig. 1), with a much smaller splitting ($\Delta=2.1$ $\mu$eV). Since this splitting corresponds[4] to a superlattice period of 52 Å , we might suggest the following model for the observed exciton: an exciton which is trapped at the "right" interface, in which the hole is trapped at a distance from the electron equal to about twice the local period (exc$R2$, shown in the upper part of Fig. 1). In spectrum 2 in Fig. 1, which was recorded at the higher optical-excitation power, we can clearly see a relative intensification of the electron signal and a change in the relative intensities of the signals of excitons exc$L1$ and exc$R2$.

To prove that excitons exc$L1$ and exc$R2$ are trapped at opposite interfaces, we studied signals representing the anticrossing of exciton energy levels. We have mentioned previously[4,9] that the method of anticrossing spectroscopy is highly informative. The anticrossing signals do not depend on the microwave field. They can be detected from changes in the intensity, circular polarization, or linear polarization of luminescence. The latter possibility exists only if there is a difference between the concentrations of ex-

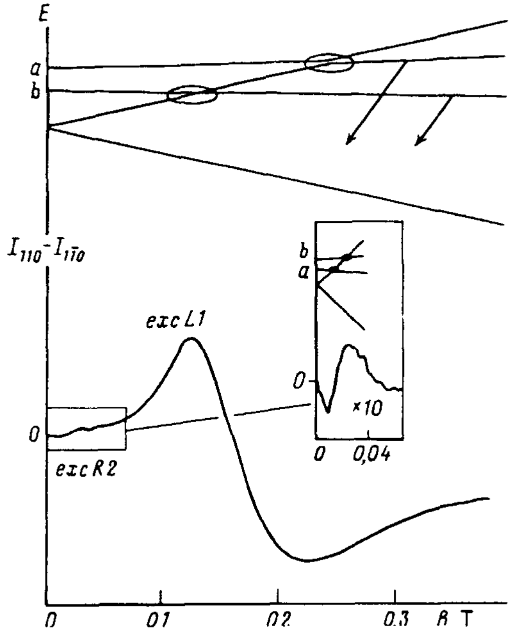

FIG. 2. System of energy levels of excitons in the anticrossing region, along with anticrossing signals detected from the linear polarization of the luminescence in sample $K$115. The inset shows the anticrossing and the system of energy levels for an exc$R$2 exciton. $T=1.6$ K, $B\parallel[001]$.

change splittings $\Delta$ of the excitons trapped at the opposite interfaces. Figure 2 shows the system of exciton energy levels in the anticrossing region along with anticrossing signals extracted from the linear polarization of the luminescence. The excitons trapped at opposite interfaces are characterized by radiative sublevels (a and b in Fig. 2) which are dipole-active in the [110] and $[1\bar{1}0]$ directions. The order of these levels is different for the opposite interfaces. The anticrossing signals in the linear polarization should thus have opposite signs. This is just what we see in Fig. 2: The signs of the anticrossing signals are opposite for exc$L$1 (large $\Delta$) and exc$R$2 (small $\Delta$). The inset in Fig. 2 shows an anticrossing signal and the system of energy levels for exc$R$2. We should mention that, since the time scales of recombination processes should not affect the intensity of anticrossing signals, the relation between the intensities of the anticrossing signals of exc$L$1 and exc$R$2 reflects the relation between the concentrations of these excitons in the superlattice. It can be seen from Fig. 2 that the concentration of exc$L$1 is more than an order of magnitude higher than that of exc$R$2. On the other hand, the approximately equal intensities of the ODMR signals of these two excitons are evidence that the lifetime of the exc$R$2 excitons is far longer.

Further support for our conclusion regarding the trapping of excitons at different interfaces comes from the experiments on superlattice $K$111, whose structure is shown in the upper part of Fig. 3. We see in Fig. 3 that the sign of the level-anticrossing signals for superlattice $K$111 is opposite the sign of the anticrossing in sample $K$115; i.e., the exciton with the larger exchange interaction is trapped at the right interface (exc$R$1), while the exciton with the smaller exchange interaction is trapped at the left interface (exc$L$2). The anticrossing signal for exc$L$2 is not seen in Fig. 3, because it is faint. The value of $\Delta$ for exc$R$1 in superlattice $K$111 (19 $\mu$eV) is slightly smaller than that for exc$L$1 in superlat-

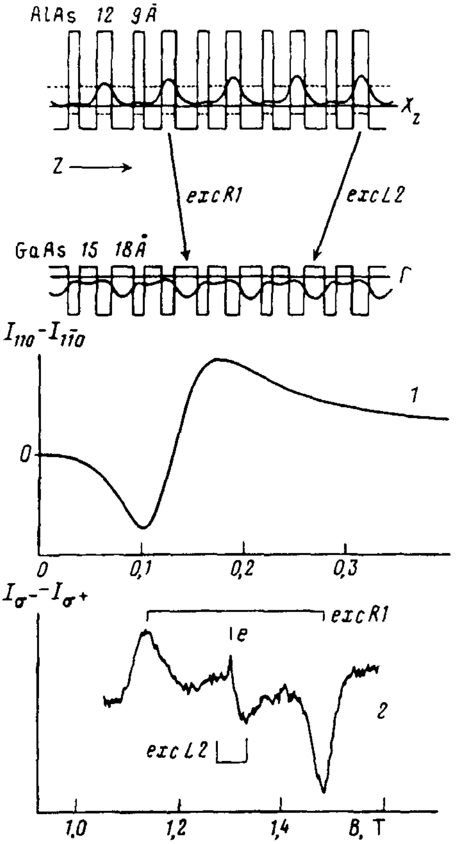

FIG. 3. Anticrossing signal extracted from the linear polarization of the luminescence (1) and ODMR spectrum at a frequency of 35 GHz extracted from the circular polarization of the luminescence (2). Sample $K111$, $T=1.6$ K, $B\|[001]$. The structure of the test sample and the recombination processes are shown in the upper part of this figure.

tice $K115$, apparently because of the imperfect equivalence of the thicknesses of the layers in these superlattices, as mentioned above. We also found the splittings of the radiative levels of excitons from the anticrossing and ODMR spectra. These splittings turn out to be 12, 1.1, 9, and 1.2 $\mu$eV for excitons exc$L1$, exc$R2$, exc$R1$, and exc$L2$, respectively.

In summary, two classes of excitons, trapped at opposite interfaces, have been observed selectively. The parameters of the spin Hamiltonian of these excitons have been determined. It has been shown that by detecting an anticrossing of exciton levels from the linear polarization of luminescence one can unambiguously identify the interface at which the exciton is trapped. The work carried out at the Ioffe Physicotechnical Institute of the Russian Academy of Sciences was supported in part by the Volkswagen Foundation (Project 1/68517) and by the Russian Fund for Fundamental Research (Project G 03-02-2603).

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