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## Dynamic properties of excitons in GaAs/AlAs superlattices from optically detected magnetic resonance and level anticrossing

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**Abstract.** Level-anticrossing measurements in linearly polarized light and ODMR recorded with different microwave chopping frequencies allowed to distinguish between excitons with different dynamic properties and to study their spectral variations in type II GaAs/AlAs superlattices.

### Introduction

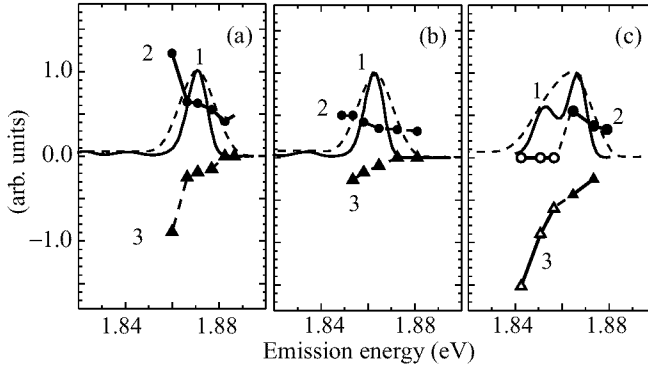
Optical detection of magnetic resonance (ODMR) and exciton level-anticrossing (LAC) allowed exact determination of electron and hole  $g$ -factors and direct measurements of the exciton exchange splittings in both type II and type I GaAs/AlAs superlattices (SL) with sub- $\mu\text{eV}$  resolution (see [1-3] and references therein). The obtained experimental dependencies can be applied for characterization of the SL period and the QW width [4]. A direct link between the order of the exciton radiative levels and the interface, normal (AlAs on GaAs) or inverted (GaAs on AlAs), was established in [5]. The lowest radiative level is  $[110]$ -polarized for excitons at the normal interface and  $[1\bar{1}0]$ -polarized for excitons at the inverted interface. This made possible separate investigations of the opposite interfaces in type II SL [6].

Since both ODMR and LAC signals are sensitive to the interplay of optical and microwave pumping, radiation and relaxation rates, these techniques can be applied to a study of exciton dynamics. In the present paper, we report on a LAC and ODMR study which demonstrates a variation of dynamic properties of excitons in type II SLs as a function of the emission energy and exciton localization.

### 1 Experimental results and discussion

Three SLs with the same nominal composition ( $1.73 \text{ \AA}$  GaAs/ $2.65 \text{ \AA}$  AlAs) were grown by MBE with the substrate kept at  $620^\circ\text{C}$  both without interruptions (sample P90) and with 30 s interruptions after AlAs layers (P91) and GaAs layers (P92). The actual composition of the samples was controlled by ODMR and Raman characterization. LAC was recorded by monitoring the  $[110]$  and  $[1\bar{1}0]$  components of emission. 24 and 35 GHz ODMR spectra were obtained by monitoring microwave-induced variations of one of circularly polarized components of luminescence with chopping of microwaves at 10 Hz–100 kHz and a lock-in detection.

At anticrossing of a highly populated non-radiative level with a depopulated radiative one exciton emission with the polarization corresponding to the radiative level increases

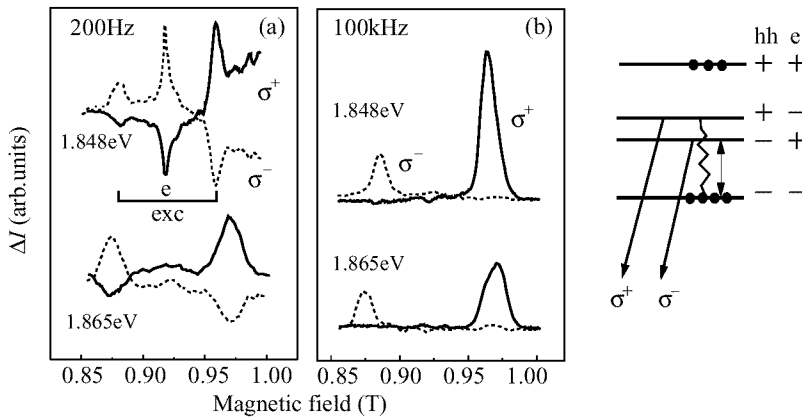


**Fig 1.** Emission spectra (curves 1), the ratio of the amplitude of “direct” LAC signals of the excitons localized at the normal interface to that for excitons localized at the inverted interface (curves 2) and the ratio of “indirect” to “direct” LAC amplitudes for excitons localized at the inverted interfaces (curves 3) in samples P90 (a), P91 (b) and P92 (c).  $T = 1.6$  K.

giving rise to a positive LAC signal which we call “direct”. At the same time population of the another radiative level with the opposite polarization can decrease due to relaxation, which produces a negative “indirect” LAC. Existence of such LAC signals [6] follows from the solution of rate equations derived in [7]. Fig. 1 shows emission spectra (curves 1), the ratio of the amplitudes of “direct” LAC signals for excitons localized at the normal interface to that for excitons localized at the inverted interface (curves 2) and the ratio of “direct” and “indirect” LAC signals (curves 3) for the samples P90, P91, P92. In the latter case the ratio is negative. Dotted lines are the emission spectra taken with a reduced spectral resolution which was used while detecting LAC.

Curves 2 in Fig. 1(a,b,c) show that in all samples excitons are preferentially localized at the inverted interface, the relative concentration of excitons at the normal interface increases with the decrease of the emission energy. The ratio of the normal to inverted excitons in the centre of the emission lines are 0.6 for P90 and 0.35 for P91. For low- and high-energy emission lines in P92 the ratio is about 0 and 0.5, respectively, i.e. there is no or very few excitons localized at the normal interface within the low energy emission line. Curves 3 in Fig. 1 (a,b,c) reveal changes in the interplay of the radiation and relaxation times. The effect of relaxation between the exciton levels which produces indirect LAC is more pronounced at the low-energy side of the emission lines in P90 and P91. The relaxation effects are the largest for the low-energy line of P92.

Different dynamic properties of excitons in SL grown with interruptions after GaAs layers were confirmed by ODMR. Fig. 2 shows ODMR recorded in P92 by monitoring  $\sigma^+$  and  $\sigma^-$  — emission components with microwave chopping frequencies  $f = 200$  Hz and 100 kHz. Two ODMR lines marked as “exc.” correspond to exciton electron spin-flips and are split by the exchange interaction [1-3]. The line in the center (“e”) belongs to electrons in distant electron-hole pairs [1, 2]. Microwave-induced resonant transitions between a more populated non-radiative exciton level and a depopulated radiative one increase emission from the latter (see inset in Fig. 2). At low chopping frequency magnetic resonance is detected as variation of both circularly polarized components of emission since due to relaxation “indirect” ODMR signals are observed. At high



**Fig 2.** ODMR for two luminescence lines in P92 recorded with the microwave chopping frequency 200 Hz (a) and 100 kHz (b) by monitoring the intensity of two circularly polarized emission components. Inset shows the exciton energy levels and resonant transition for low-field exciton ODMR line.  $\nu = 24$  GHz.  $B \parallel [001]$ .

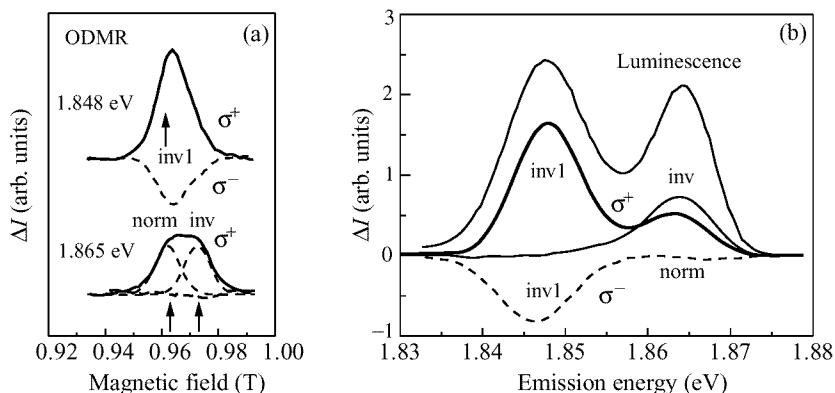
chopping frequency ODMR is manifested in one polarization as expected in case of slow relaxation.

By choosing an appropriate microwave chopping frequency one can separate exciton and electron-hole recombination. Electron ODMR signal disappears at  $f > 1\text{--}2$  kHz which implies longer radiative and relaxation times of such a recombination. 35 GHz ODMR of exciton holes was detected at  $f = 390$  Hz and microwave power 400 mW while only “unbound” hole ODMR was seen at lower power (10 mW).

The high-field ODMR signals of excitons obtained with  $f = 10$  kHz are shown in Fig. 3(a). ODMR recorded within the emission line 1.865 eV is a superposition of two signals which belong to excitons localized at the normal and inverted interfaces. For both excitons there is no “indirect” ODMR in  $\sigma^-$  polarization. This means that the relaxation times are larger than the radiative times and modulation period. The low-energy emission line 1.848 eV belongs to excitons localized at the inverted interface in the region of monolayer-step GaAs islands [6]. The behavior of ODMR of these excitons is different: “indirect” ODMR disappears for  $f > 30$  kHz only. This implies that for such excitons hole relaxation is much faster in agreement with the results of measurements of the “indirect” LAC signals. The reason of such a different behavior is still not completely understood and requires further studies.

Spectral dependencies of ODMR are shown in Fig. 3(b). Although the resonance fields for excitons “norm” and “inv1” coincide it is possible to resolve their emission lines since there is no ODMR in  $\sigma^-$ -polarization for excitons “norm”.

In conclusion, LAC measurements in linearly polarized light and ODMR recorded with different microwave chopping frequencies allowed to distinguish between excitons with different dynamic properties and to study their spectral variations in type II GaAs/AlAs SL. A drastic difference in the exciton localization at normal and inverted interfaces and their dynamic behavior was found for excitons in a SL grown with interruptions after GaAs layers. Exciton and electron-hole recombination was resolved due



**Fig 3.** (a) ODMR recorded with chopping at 10 kHz by monitoring two circularly polarized emission components within the peaks of emission lines in P92; (b) spectral variations of the ODMR signals.

to their different characteristic times. Time-resolved ODMR measurements in which ODMR is detected with a time delay relative to the light excitation pulse seem to be very promising for an investigation of exciton dynamics and are in progress.

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