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Electron g-factor in GaAs/AlGaAs quantum wells of different width and barrier Al concentrations.

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Abstract. Using electrically detected electron spin resonance technique, three components of electron g-factor tensor are studied in a number of asymmetrically doped GaAs/AlGaAs quantum wells grown in the [001] direction. The investigated quantum wells are characterized by different well widths and barrier Al concentrations. The dependence of g_{zz} component along the growth direction on the heterostructure band gap was shown to be universal. The band gap was measured with the aid of photoluminescence. The two-fold in-plane g-factor anisotropy with the [110] and [$1\overline{1}0$] principal axes turned out to vanish in narrow quantum wells. Three nonzero components of $\hat{a}$ tensor of the linear in the magnetic field corrections to the g-factor are measured for a number of wells of different parameters. The $\hat{a}$ tensor components are strongly dependent on the well width.

The energy of spin-splitting is usually described by the Landé g-factor. In bulk zincblende semiconductors spin splitting is isotropic and the g-factor is reduced to a scalar. The value of the g-factor is strongly dependent on the band gap energy of the crystal [1, 2]. In systems with low symmetry the electron g-factor turns out to be a tensor with several independent components. Thus, in symmetric GaAs/AlGaAs quantum wells grown along the [001] crystallographic direction the g-factor component perpendicular to the plane of the two-dimensional electron gas differs from the one parallel to this plane. Moreover, the strong two-fold in-plane anisotropy of the electron g-factor was observed in asymmetric quantum wells grown in the same direction [3, 4, 5, 6, 7].

As was shown elsewhere [3, 4, 8, 9], the g-factor in asymmetric wells is dependent on the orientation, as well as on the magnitude of the magnetic field. These dependences may be described by the tensor $\hat{a}$ of the first-order corrections in the magnetic field. In our previous work [3, 4], this tensor was shown to have at least three nonzero components, namely a_{xxz}, a_{yyz}, a_{zzz}, where the Ox, Oy and Oz axes correspond to the [110], [$1\overline{1}0$] and [001] directions respectively. All components of the $\hat{g}$ and $\hat{a}$ tensors are strongly dependent on the quantum well parameters, such as well widths and barrier Al concentration. The present paper aims to investigate the in-plane and out-of-plane g-factor anisotropies and to determine the influence of heterostructure parameters on both tensors discussed.

Studies of electron g-factor in GaAs quantum wells have been performed with the aid of several experimental methods: quantum beating spectroscopy, Kerr rotation and electrically detected electron spin resonance techniques. Let us note that optical techniques [10, 11] were mainly

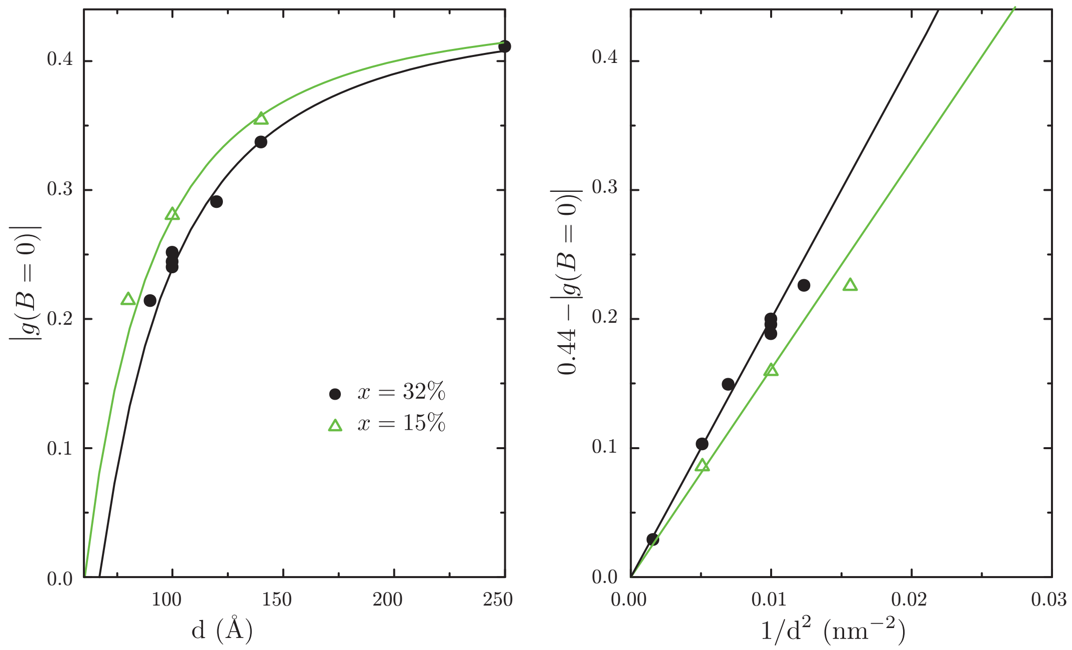

Figure 1. On the left panel the value of the electron g-factor perpendicular to the plane (g_{zz}) of the two-dimensional electron gas measured in two series of quantum wells is plotted vs the width. In each of the series the width of the quantum well was varied, whereas the barrier Al concentration was approximately the same. On the right panel the difference between the bulk GaAs g-factor and the measured value of g_{zz} is depicted vs the inverse well width squared. Solid lines represent the simple model described in the text.

used for the investigation of nominally undoped quantum wells. The g-factor tensor in such wells was theoretically calculated in [12, 13]. In a recent paper [14] the universal dependence of the out-of-plane g-factor component on the quantum well energy gap was revealed in symmetric, nominally undoped, quantum wells. On the contrary, asymmetrically doped GaAs/AlGaAs heterostructures are under investigation in the present paper. The electrically detected electron spin resonance (ESR) technique is particularly suitable for precise measurements of electron g-factor in such wells. For example, this method was successfully applied for the investigation of ESR at subunity filling factors [15] and the spin-exciton relaxation rate [16] in the two-dimensional Hall ferromagnet. In the previous papers we have demonstrated that ESR technique can be utilized for precise measurements of the g-factor and the first-order terms of the g-factor dependence on the magnetic field [3, 4].

The conventional ESR technique cannot be successfully applied to 2D electron systems [17] due to the low number of spins. However, the magnetoresistance of the 2DEG was shown [18] to be very sensitive to spin resonance when the Fermi level is located between spin-split states of a given Landau level. Having measured the fraction δR_{xx} of the magnetoresistance R_{xx}, arising due to the RF absorption, it is possible to observe spin resonance as a peak in $R_{xx}(B)$ at a fixed RF frequency. According to the Larmour theorem, since the RF wave vectors are much smaller than the reciprocal magnetic length, the excitonic effects do not significantly affect spin splitting and, thus, the experimentally measured g-factor corresponds to the single-particle limit.

Several $Al_xGa_{1-x}As/GaAs$ quantum wells of different width and barrier Al concentration were studied. All of them were grown in the [001] direction by MBE. All quantum wells were asymmetrically δ-doped with Si. The electron density varied from $1.2 \times 10^{11} cm^{-2}$ to

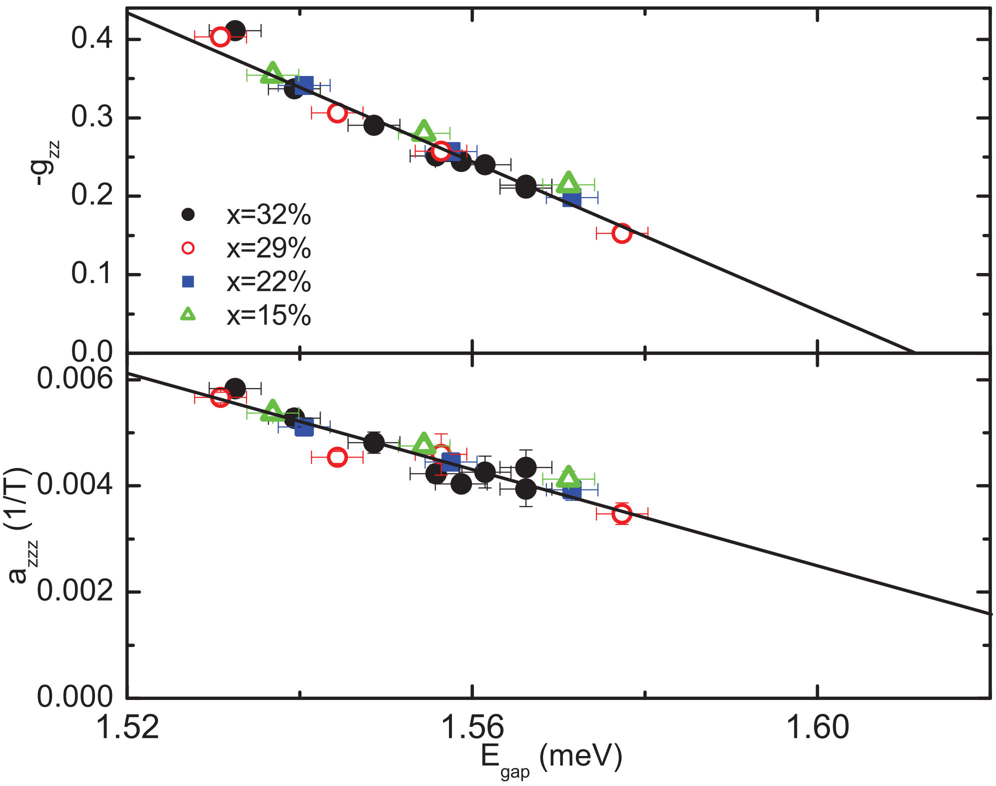

Figure 2. The absolute values of g_{zz} and a_{zzz} (the term representing the dependence of g_{zz} on the magnetic field perpendicular to the plane of two-dimensional electron gas) are plotted vs the quantum well band gap. The band gap energies were measured with the aid of photoluminescence.

$4.4 \times 10^{11} cm^{-2}$ and the mobilities ranged from $0.3 \times 10^5\ V/(cm^2 s)$ up to $10 \times 10^5\ V/(cm^2 s)$. On all of the samples usual Hall bar mesas were prepared. The barrier Al concentration and the quantum well band gap were checked with the aid of photoluminescence.

An ac probe current of 1μA at the frequency of $\sim$1 kHz was applied from source to drain of the sample under investigation. A lock-in amplifier monitored the channel resistance R_{xx} through two sense contacts along the channel. The sample was illuminated by 100% amplitude modulated radiation at the frequency of f_{mod} $\sim$30 Hz; RF power was delivered from the generator through a coaxial cable terminated by a loop antenna. The second lock-in amplifier, synchronized at the frequency of f_{mod}, was connected to the demodulated output of the first one and, thus, measured the change δR_{xx} in the magnetoresistance, caused by microwave irradiation.

Experiments were carried out at temperatures of $1.3 - 4.2$ K in magnetic fields up to 10 T. In our experiments, we fixed the microwave frequency and swept the magnetic field. In [16], we showed that the results of ESR measurements using frequency and magnetic field sweeps do coincide, but the magnetic field sweep is much more convenient in the experiment. From the magnetic field dependence of the ESR-frequency we extracted the g-factor value and its

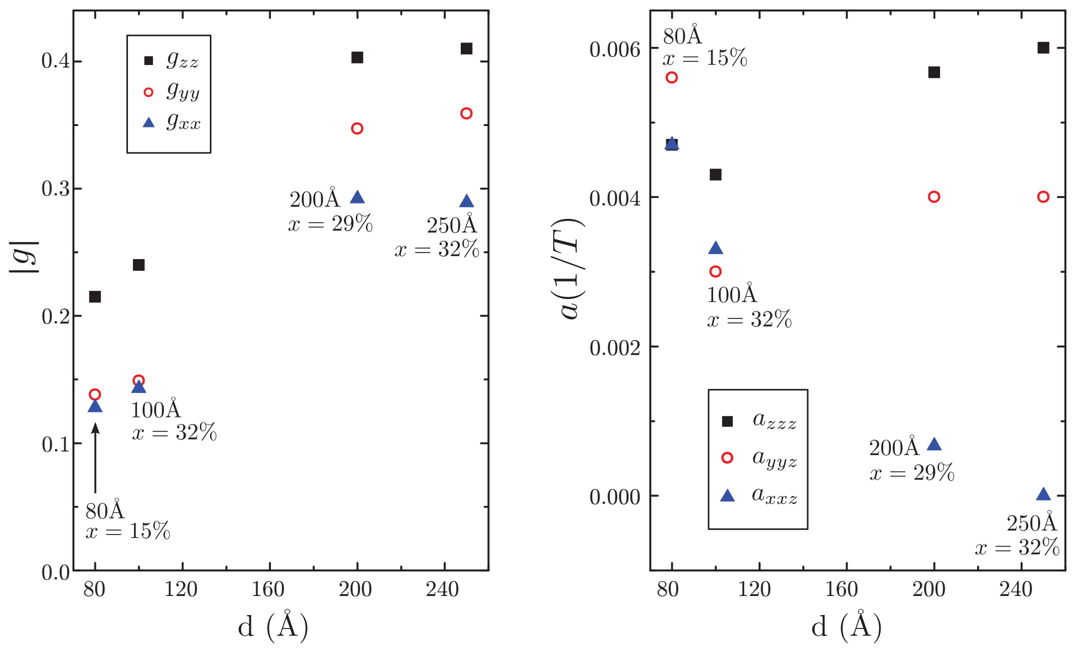

Figure 3. The magnitudes of all three diagonal components of the $\hat{g}$ tensor and three nonzero components of the $\hat{a}$ tensor measured in a number of quantum wells characterized by different well widths and barrier Al concentrations.

dependence on the magnetic field. The linear extrapolation of $g(B)$ dependence to zero magnetic field gives us the $g(B = 0)$, that is the g-factor for the subband bottom. The justification of this procedure can be found in our previous papers, e.g. [3]. The results of the measurements of the out-of-plane component g_{zz} in two series of samples characterized by various well widths are presented in Fig. 1. The barrier Al concentration was approximately the same in each of the series of samples, namely $x = 15\%$ (open triangles) and $x = 32\%$ (solid circles). The accuracy of the $g(B = 0)$ absolute value was typically 0.002, whereas the accuracy in the well-width corresponds to one monolayer. Thus, the errors in Fig. 1 are smaller than the symbols size. Three circles at the well width $d = 100$Å in Fig. 1 correspond to three samples independently grown and having small variation of the Al-content (about 1%) and the well width (one monolayer) one from another, as shown with the aid of photoluminescence technique.

The values of g_{zz} turned out to depend strongly on well widths. This can be easily explained by the dependence of quantum well band gap energy on the well width d. This phenomenon can be taken into account by utilizing a simple model: the electron g-factor depends on the band gap energy of the material [1]; the band gap energy of the heterostructure in turn is equal to the sum of the GaAs bulk band gap energy and a term proportional to $1/d^2$ (in the approximation of a rectangular well with infinite walls); if this term is small enough, the g-factor dependence on the band gap energy of the heterostructure is close to linear. The difference between the bulk $g = -0.44$ and the measured g-factor is depicted versus $1/d^2$ in the right panel of Fig. 1. Solid lines in Fig. 1 represent this model. As can be seen, the model is valid for wide wells but fails in narrow structures. In fact, the band gap energy depends on the heterostructure parameters in a more complicated manner than assumed in this simplified model. Moreover, the g_{zz} dependences on the quantum well width do not coincide in these two series of samples. This may be ascribed to the difference of the band gap energies in two wells of the same width, if the Al concentration is varied.

All the facts mentioned above suggest to measure directly the quantum well band gap and to plot the g-factor against this energy value. The results are presented in Fig. 2. As can be seen, the dependence of g_{zz} on the band gap energy turned out to be universal. What is more surprising, the dependence of a_{zzz} (the term describing the correction to g_{zz} linear in B_z) is also universal. The g_{zz} value reaches zero at some value of energy, whereas a_{zzz} remains finite. This result suggests that in some quantum wells with nonzero g_{zz} at zero magnetic field g_{zz} can reach zero and even change its sign when a moderate magnetic field is applied. The magnitude of such a field diminishes with the increase of quantum well band gap energy. This effect may be utilized as a technique of spin manipulation. In quantum wells the barrier region contributes to the total g-factor. The amount of the wave function penetrating into the barrier and the g-factor in the barrier depends on the potential barrier height, and, thus, the total g-factor value does depend on the Al concentration in the barrier region. Moreover, if the electron density is varied, the well potential profile and the amount of wave function penetrating into the barrier changes. The difference in such well parameters might be responsible for the slight deviations of the g_{zz} and of the a_{zzz} values from universal behavior.

In Fig. 3 the results of $\hat{g}$ and $\hat{a}$ measurements in a number of samples are presented. Parameters of the structures are shown on the plot. As can be seen, the in-plane g-factor anisotropy is strong in wide wells and practically vanishes in narrow ones, whereas the difference between the in-plane and out-of-plane components of the g-factor remains prominent in all of the samples measured. Similarly, the difference between the components of $\hat{a}$ tensor decreases in narrower wells. As can be seen from Fig. 3, the a_{zzz}, g_{zz} and g_{xx} components diminish with well narrowing, whereas a_{xxz} does not. Thus, the magnetic field at which $g_{xx} = 0$ is lower than the field required to make $g_{zz} = 0$. In narrower wells the electron wave function along the growth direction tends to be more symmetric than in wider ones. This might be responsible for the observed reduction of the in-plane anisotropy of the g-factor, since this anisotropy vanishes in symmetric wells [5].

In conclusion, three components of the electron g-factor tensor were measured in a number of asymmetrically doped GaAs/AlGaAs quantum wells grown in the [001] direction. The quantum wells were characterized by different well widths and barrier Al concentrations. The dependences of g_{zz} and a_{zzz} components along the growth direction on the heterostructure band gap were shown to be universal. The two-fold in-plane g-factor anisotropy was shown to vanish in narrow quantum wells. Three nonzero components of $\hat{a}$ tensor of the linear in the magnetic field corrections to the g-factor are measured in several samples. The $\hat{a}$ tensor components are strongly dependent on the well width. The magnetic field required for g_{zz} to reach zero and to change its sign is lower in quantum wells with higher band gap energy. In narrow wells g_{xx} goes to zero at smaller magnetic field than g_{zz}. These findings may facilitate electron spin manipulation with the aid of the magnetic field.

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