# Anisotropy of the electron $g$-factor in GaAs/AlGaAs quantum wells

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(Submitted 27 July 1992)
Pis'ma Zh. Eksp. Teor. Fiz. **56**, No. 5, 257–263 (10 September 1992)

An anisotropy of the $g$-factor of conduction electrons has been detected in single $GaAs/Al_{0.3}Ga_{0.7}As$ quantum wells on the basis of a magnetic depolarization of luminescence during optical orientation of the electrons. A ratio $g_{\parallel}/g_{\perp} = 2.2 \pm 0.4$ was measured in a quantum well 80 Å wide, where $g_{\parallel}$ and $g_{\perp}$ are the components of the $g$-factor along and across the principal axis of the structure. A bistability of the spin-coupled electron-nuclear spin system of the semiconductor has been detected. This bistability results from an anisotropy of the electron $g$-factor. It is manifested in a hysteresis on the curve of the magnetic depolarization of the luminescence.

In a bulk semiconductor of the GaAs type, a conduction electron has an isotropic $g$-factor. In heterostructures with quantum wells, the quantum size effect renders the $g$-factor of the conduction electrons anisotropic, as was shown theoretically in Ref. 1. In the GaAs/AlGaAs system, in which $g_{\parallel}$ and $g_{\perp}$ cross zero with decreasing well width,[1,2] the anisotropy parameter becomes anomalously large.[1] A difference between $g_{\parallel}$ and $g_{\perp}$ in short-period superlattices was observed in Ref. 3. In the present study we have carried out the first measurements of the anisotropy parameter of the electron $g$-factor in a single rectangular $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well. In a well of width $L_z = 80$ Å, this anisotropy parameter is found to be $g_{\parallel}/g_{\perp} = 2.2 \pm 0.4$. We show that the anisotropy of $g$ leads to a qualitatively different behavior of the electron-nuclear spin system of the semiconductor under optical-orientation conditions. In particular, as the angle between the magnetic field and the plane of the quantum well is increased, the electron-nuclear spin system becomes bistable. This bistability is manifested in a hysteresis on the curve of the magnetic depolarization of the luminescence.

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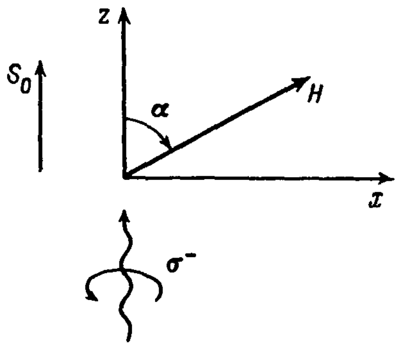


FIG. 1. The experimental geometry. Here $S_0$ is the average spin of the optically oriented electrons in a zero magnetic field.

**1.** When a semiconductor is excited by circularly polarized ($\sigma^{\pm}$) light, the conduction electrons acquire an average spin[4] **S**. Let us examine the dependence of the $z$ component ($S_z$) of the spin **S** on the strength of an external magnetic field $H$ directed at an angle $\alpha$ with respect to the ray of exciting light (with respect to the $z$ axis; Fig. 1). In a crystal with an isotropic electron $g$-factor, the projection of **S** onto **H** in a field $H\to\infty$ is $S_H = S_0 \cos\alpha$. In this case we have $S_z = S_H \cos\alpha$ and therefore $S_z/S_0 = \cos^2\alpha$. In the case of an anisotropic $g$, the precession axis for the electron spins does not coincide with the direction of the field **H**, and as $H\to\infty$ we have $H\to\infty$ $S_z/S_0 = \cos^2\alpha$. The difference between $S_z/S_0$ and $\cos^2\alpha$ is determined by the ratio of $g_{\parallel}$ and $g_{\perp}$; this difference can be utilized to determine the anisotropy parameter $g_{\parallel}/g_{\perp}$.

To find an analytic expression for $S_z$ in terms of $g_{\parallel}/g_{\perp}$ and $\cos\alpha$, we use a steady-state equation for the average electron spin **S** in a bulk semiconductor.[4] We assume that the electron $g$-factor in the semiconductor is anisotropic:

$$\frac{\mathbf{S}-\mathbf{S}_0}{T_s} = \frac{\mu_B}{\hbar}\hat{g}\mathbf{H}\times\mathbf{S} + \frac{A\langle\mathbf{I}\rangle}{\hbar}\times\mathbf{S}. \tag{1}$$

Here $\hat{g}$ is a second-rank tensor with nonzero diagonal elements $g_{\perp}\equiv g_{xx}\equiv g_{yy}$, $g_{\parallel}\equiv g_{zz}$; the Bohr magneton satisfies $\mu_B>0$; and $T_s$ is the duration of the optical orientation, which is given by $1/T_s = 1/\tau + 1/\tau_s$, where $\tau$ and $\tau_s$ are the lifetime and the spin relaxation time of the electrons. The first term on the right side of (1) describes the precession of the electron spins in the external magnetic field **H** at a frequency $\vec{\Omega} = \mu_B\hat{g}\mathbf{H}/\hbar$. The second term describes that which occurs in the field of the polarized nuclei of the crystal lattice, $H_N = \hat{g}^{-1}A\langle\mathbf{I}\rangle/\mu_B$ at a frequency $\vec{\Omega}_N = A\langle\mathbf{I}\rangle/\hbar$ ($\langle\mathbf{I}\rangle$ is the average spin of the nuclei, and $A$ is the hyperfine interaction constant).

At first we ignore the hyperfine interaction of the electrons and the nuclei ($\langle\mathbf{I}\rangle=0$). In the strong-field case, $H\gg H_{1/2}$ ($H_{1/2}=\hbar/|g_{\perp}|\mu_B T_s$ is the half-width of the Hanle effect in a transverse magnetic field), in which we are interested here, we find from (1)

$$\frac{S_z}{S_0} = \frac{a^2}{a^2+\tan^2\alpha}, \tag{2}$$

where $a = |g_{\parallel}|/|g_{\perp}|$. We see that with $a\neq 1$, the value of $S_z/S_0$ is indeed different from $\cos^2\alpha$.

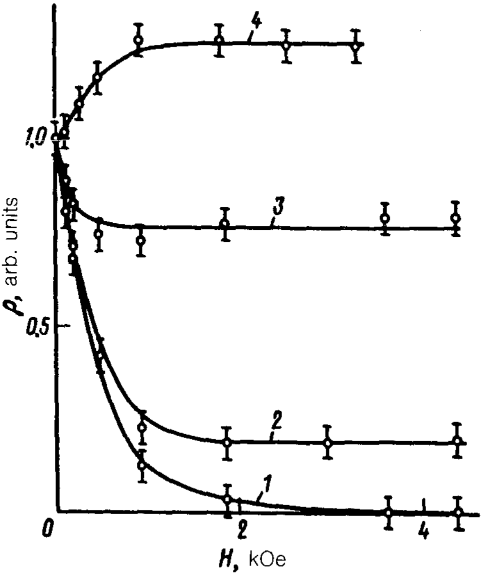


FIG. 2. Experimental results on $\rho(H)$ obtained with exciting light whose circular polarization was varied at a frequency of 34 kHz, at $T = 2$ K. $\alpha$: *1*—90°; *2*—80°; *3*—60°; *4*—0°. The solid curves are drawn for clarity.

An experiment was carried out on a heterostructure grown by the MOS hydride epitaxy method in the [001] direction (along the $z$ axis). The structure contained 30 layers of GaAs, each 80 Å thick, separated by 400-Å $Al_{0.3}Ga_{0.7}As$ barriers.[5] The optical orientation of the quasi-2D electrons in the GaAs layers was carried out with circularly polarized light with a wavelength $\lambda = 7525$ Å. The measured quantity was the degree of circular polarization of the luminescence ($\rho$), which was measured in a reflection arrangement along the $z$ axis. In crystals of the GaAs type we have[4] $\rho \propto S_z$. We analyzed the luminescence due to transitions to acceptor levels. The arrangement of Ref. 6 was used for the measurements of $\rho$. To eliminate nuclear effects, we varied the sign of the circular polarization of the exciting light at a high frequency (34 kHz). In this case there is no dynamic nuclear polarization, since this polarization cannot keep up with the rapid changes in the direction of **S**.

Figure 2 shows the experimental $\rho(H)$ dependence for various angles $\alpha$. As the magnetic field is strengthened, the values of $\rho$ approach a constant level $\rho^*(\alpha)$ (constant within the experimental errors). For $\alpha \neq 0°$, this constant level is higher than $\cos^2\alpha$. For example, we find $\rho^*(60°) = 0.80 \pm 0.05$, in comparison with $\cos^2 60° = 0.25$. Curve *4* in Fig. 2 was found in a longitudinal field $\mathbf{H} \| \mathbf{S}_0$. We see from these results that $\rho$ increases with increasing $H$. This increase in $\rho$ is due to a slowing of the electron spin relaxation.[4] In the determination of the anisotropy parameter $g_\| / g_\perp$ from the values of $\rho^*(\alpha)$, this slowing was taken into account by normalizing $\rho^*(\alpha)$ to $\rho^*(\alpha = 0) = 1.25 \pm 0.05$. Using (2), with $S_z/S_0$ replaced by $\rho^*(\alpha)/\rho^*(0)$, we find $a = |g_\| | / |g_\perp| = 2.2 \pm 0.4$. The value found for $|g_\| | / |g_\perp|$ agrees quantitatively with the result calculated in Ref. 1.

It was shown in Ref. 7 that the quantum size effect can lead to an anisotropy of the electron spin-relaxation time $\tau_S$ in a quantum well. In this case, the parameter $a$ in (2) will also depend on the anisotropy of $\tau_S$, as can be seen easily. In the structure studied in the present experiments, however, the anisotropy of $\tau_S$ can be ignored. This conclusion is based on the results of experiments on the optical polarization of lattice nuclei of the crystal; these results are analyzed in the following section of this paper.

**2.** The hyperfine interaction of optically oriented electrons with nuclei is accompanied by a dynamic polarization of the nuclei of the crystal lattice of a semiconductor.[4] In turn, the polarized nuclei create a magnetic field $H_N$ (the Overhauser field), which acts on the electron spins. As a result, $\rho$ is a complex function of $H$.

The field of nuclei, $\mathbf{H}_N$, can be seen most clearly in an oblique-field arrangement (Fig. 1). In this case this field either strengthens or weakens the effect of the component of $\mathbf{H}$ perpendicular to $\mathbf{S}$. In bulk GaAs in fields $H \gg H_L$ (the local field produced at a nucleus by the neighboring nuclei is $H_L \sim 1$ Oe), the nuclear field is in the direction $\mathbf{H}_N \| \mathbf{H}$. The electron spins are then in the resultant field $(H + H_N)$, and the Hanle curve shifts by an amount $H = -H_N$. Since we have $H_N \propto S_H = S_0 \cos \alpha$, the value of $H_N$ and the shift of the Hanle curve are determined by the angle $\alpha$ (Ref. 4).

Figure 3 shows experimental results on $\rho(H)$ found in this quantum-well struc-

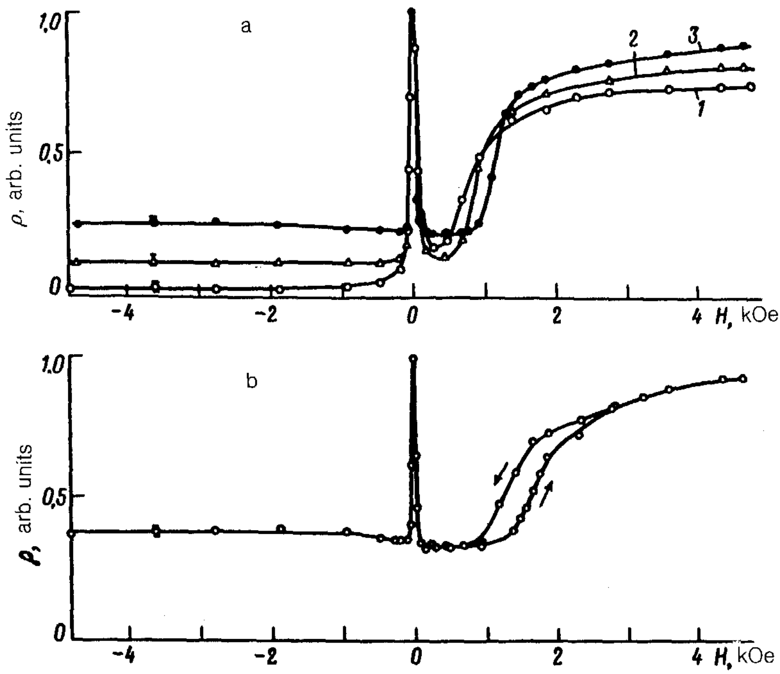


FIG. 3. Experimental $\rho(H)$ curves recorded at $T = 2$ K at a constant circular polarization of the exciting light. a: $\alpha = 85°$, 80°, and 70° (curves *1–3*, respectively). b: $\alpha = 60°$.

ture in the case of a constant circular polarization of the exciting light. On these curves we see a narrow peak near $H=0$ and a broad rise at $H \gtrsim 1$ kOe.

The narrow peak stems from the effect of the field of the optically oriented electrons (the Knight field) on the polarization of the nuclei in a weak field $H$. In this case the directions of $\mathbf{H}_N$ and $\mathbf{H}$ are not the same. This part of the Hanle curve was studied in Ref. 8, where an optical polarization of nuclei in quantum wells was first observed in an oblique field. That part of the curve will not be discussed here.

The increase in $\rho$ in fields $H \gtrsim 1$ kOe can be linked in a natural way with a cancellation of the nuclear field by the external field. However, there are several clearly defined features which cannot be explained in the model of a polarization of nuclei in bulk GaAs: (a) The width of the rise in $\rho$ at $H \gtrsim 1$ kOe is considerably greater than the half-width of the electron Hanle effect (curve *1* in Fig. 2), $H_{1/2} \simeq 0.4$ kOe. (b) This rise undergoes essentially no shift toward stronger magnetic fields as the angle $\alpha$ is raised from 85° to 60°, although $\cos\alpha$ and thus $H_N$ increase by a factor of 6. (c) As the angle between $H$ and plane of the quantum well is increased, a hysteresis appears on the $\rho(H)$ curve (Fig. 3b). (d) Away from the central peak, at $H<0$ and also $H>0$, the values of $\rho$ before the rise in $\rho$ begins are substantially smaller than the values of $\rho^*(\alpha)$ in Fig. 2 found at the same angles $\alpha$ with $H_N=0$.

These features can, on the other hand, be explained in a natural way when an anisotropy of the electron $g$-factor is taken into account.

The change caused in $\mathbf{S}$ by the polarized nuclei is described by the term $(A\langle \mathbf{I}\rangle/\hbar)\times S$ in (1). We assume that the polarization of the nuclei is isotropic, as it is in bulk GaAs. In other words, we assume that the average nuclear spin $\langle \mathbf{I}\rangle$ is directed along the external field $\mathbf{H}$ and is proportional to the projection of $\mathbf{S}$ onto this direction. If there is no leakage of nuclear polarization we have[4]

$$<\mathbf{I}> = (4/3)I(I+1)(\mathbf{S}\,\mathbf{h})\mathbf{h}, \tag{3}$$

where $I$ is the nuclear spin ($I=3/2$ for all the lattice nuclei in the structure of interest here), and $\mathbf{h}=\mathbf{H}/H$.

We used a numerical method to solve the equation obtained by substituting (3) into (1):

$$\mathbf{s} = \mathbf{s}_0 + \left[\frac{g_\perp}{|g_\perp|}\mathbf{H} + \frac{g_\parallel - g_\perp}{|g_\perp|}(\mathbf{H}\,\mathbf{k})\mathbf{k} + b(\mathbf{s}\,\mathbf{h})\mathbf{h}\right] \times \mathbf{s}. \tag{4}$$

Here $\mathbf{s}=\mathbf{S}/|S_0|$, $\mathbf{s}_0=\mathbf{S}_0/|S_0|$, and $\mathbf{k}$ is the unit vector along the $z$ axis. The parameter $b$ characterizes the precession of the electron spins in the nuclear field:

$$b = \frac{5S_0}{|g_\perp|}\frac{(A/\mu_B)}{H_{1/2}}, \tag{5}$$

where[9] $(A/\mu_B) = 15.5$ kOe.

The results of the solution of Eq. (4) depend strongly on the ratio $g_\parallel/|g_\perp|$, on the parameter $b$, and on the signs of $g_\perp$ and $(g_\parallel - g_\perp)$. The parameter $|g_\parallel|/|g_\perp| = 2.2$ is defined in Sec. 1. The signs of $g_\parallel$ and $g_\perp$ were found in the following way. A negative sign was found for $g_\perp$ from the relative positions of the additional maxima produced

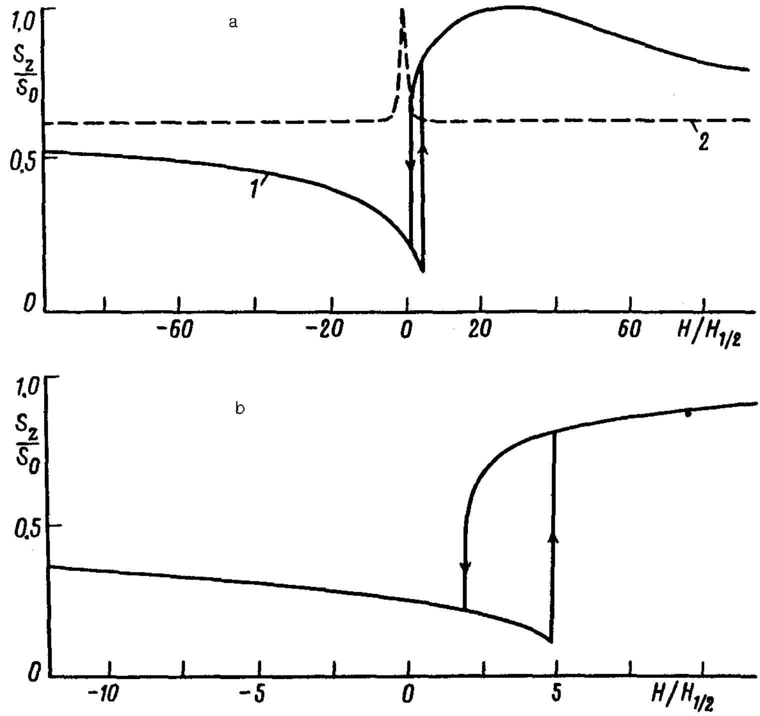


FIG. 4. Results of a numerical solution of Eq. (4) for $\alpha = 60°$, $g_{\parallel}/g_{\perp} = 2.2$, $g_{\parallel} < g_{\perp} < 0$. a: *1*—b = 60; *2*—b = 0. b: The hysteresis region on curve *1*, in larger scale along the $H$ axis.

on the experimental curves of $\rho(H)$ in Fig. 3 by the cancellation of the nuclear field and the field of the electrons by the external field.[8] A calculation shows that the theoretical Hanle curves correspond to the experimental $\rho(H)$ curves in Fig. 3 only if the relation $g_{\parallel} < g_{\perp}$ holds. There is a qualitative difference if $g_{\parallel} > g_{\perp}$. We thus conclude $g_{\parallel} < g_{\perp}$ and therefore $g_{\parallel} < 0$ and $g_{\parallel}/g_{\perp} = 2.2$. This result agrees with the prediction of the theory of Ref. 1, according to which the relation $g_{\parallel} < g_{\perp}$ would hold in a quantum well of any width, and we would have $g_{\parallel} < g_{\perp} < 0$ for $L_z = 80$ Å.

Figure 4a shows calculated curves of $S_z(H)/S_0$ for $\alpha = 60°$, $g_{\parallel} < g_{\perp} < 0$, $g_{\parallel}/g_{\perp} = 2.2$, $b = 60$ (curve *1*), and $b = 0$ (there is no nuclear polarization; curve *2*). We see that curve 1 has all the features observed above on the experimental curves of $\rho(H)$ (Fig. 3). The maximum on this curve centered at $H = 30H_{1/2}$ is thus indeed due to a cancellation of the nuclear field by the external field. Its width is two orders of magnitude greater than the width of the purely electron Hanle curve (curve *2* in Fig. 4a). Near the left boundary of the maximum we find a bistability region, which is shown in larger scale along the $H$ axis in Fig. 4b. A calculation shows that the position of the left boundary of this maximum depends only weakly on the angle $\alpha$, while the hysteresis region shrinks rapidly with increasing $\alpha$, disappearing as $\alpha$ approaches 90°.

The most interesting fact is that curve *1*, calculated with allowance for the nuclear polarization, in Fig. 4a runs below the lowest value of $S_z/S_0$ on curve *2*, plotted for $H_N = 0$, over a broad range of the field $H$. The explanation is, as follows from (1), that the precession axes of the electron spins in the nuclear field and the external field do not coincide: $\vec{\Omega}_N \| \mathbf{H}$, $\vec{\Omega} \nparallel \mathbf{H}$. For this reason, in a weak field $H \ll H_{1/2}$, in which the electrons are depolarized by the nuclear field, the value of $S_z/S_0$ decreases to $\cos^2\alpha$, which is 0.25 for $\alpha = 60°$ (Fig. 4b). This conclusion is supported by the shape of the experimental $\rho(H)$ curves in Fig. 3.

We have shown that incorporating an anisotropy of the *g*-factor makes it possible to theoretically explain the experimental dependence $\rho(H)$ in both the presence and absence of nuclear polarization. Analysis shows that, if there is an anisotropic spin-relaxation time $\tau_s$, the Hanle curves calculated with nuclear polarization are qualitatively different from those observed experimentally. It follows that we can ignore the effect of an anisotropy in $\tau_s$ in our experiments.

In this study we have thus observed an anisotropy of the electron *g*-factor in single $GaAs/Al_{0.3}Ga_{0.7}As$ quantum wells. Using an optical-orientation method, we have established that the relations $g_\| < g_\perp$ and $g_\| / g_\perp = 2.2 \pm 0.4$ hold in a well 80 Å wide. We have developed a model for the polarization of the electron-nuclear spin system, which incorporates an anisotropy of the electron *g*-factor. This model is successful in explaining aspects of the behavior of the electron-nuclear spin system in the quantum well which we studied. This model should lead to some substantially new results in narrower quantum wells, in which $g_\|$ and $g_\perp$ would differ in sign according to Ref. 1. In particular, the solution of (4) shows that in the case $g_\perp > 0$ and $g_\| < 0$ the electron nuclear spin system has two bistability regions, which exist for opposite directions of the external magnetic field.

We wish to thank B. P. Zakharchenya and V. G. Fleĭsher for constant interest in this study. We also thank E. L. Ivchenko and I. A. Merkulov for useful discussions and B. S. Yavich and O. M. Fedorova for furnishing the crystals.

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Translated by D. Parsons