

# Electric field controlled g-factor in parabolic well determined by transport measurements

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## Abstract

The Shubnikov de Haas oscillations in 500 Å parabolic well are studied in the tilted magnetic field. The electric field displaces the electron wave function along Z-axis and leads to the strong variation of the average bare g-factor in such system. From the measurements of the filling factor  $\nu_c$  at which the spin gap collapse occurs, we deduce the total Zeeman energy, which consists of the bare Zeeman energy and exchange-correlation term. By investigating of the variation of  $\nu_c$  in tilted field we reliably extract the bare g-factor as a function of the gate voltage.

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## 1. Introduction

The main idea of the quantum computing is to replace the classical bit by the quantum bit, or qubit, a quantum two-level system, which can be thought of the spin-up and spin-down states of the electron in quantum dots [1]. However, the practical implementation of these ideas requires complete control and manipulation of an individual spin by applying the static magnetic field. Therefore, each spin must have an individual set of coils producing such fields, and each spin must be shielded from fields from other spins. This very challenging problem can be excluded, if we are able to manipulate with the electron g-factor, in particular its sign, by applying the electric field. In this case the direction of the spin polarization of electrons in individual dot can be varied by local electric field in the uniform external magnetic field.

Promising system providing effective control and manipulation with the electron spin is a remotely doped

$\text{Al}_x\text{Ga}_{1-x}\text{As}$  parabolic quantum well, because the spin properties of such materials depend strongly on the Al composition  $x$ . In perpendicular magnetic field g-factor should be calculated by averaging the local g-factor along the Z-axis:

$$\langle g \rangle = \frac{1}{W} \int g(Z) |\Psi(Z)|^2 dZ, \quad (1)$$

where  $\Psi(Z)$  is the electron wave function. Application of the strong perpendicular magnetic field leads to the Zeeman splitting of the Landau levels (LL), which is proportional to the average g-factor in parabolic well. Recently, spin precessions of 2D electron gas in 1000 Å parabolic well has been measured from photoluminescence as a function of the gate voltage [2]. The electric field displaces the electron wave function along Z-axis and leads to the strong variation of the average g-factor, and consequently, variation of the spin lifetime. This ability to tune the local electron g-factor allows to fabricate in principle a logic gate for quantum computing, however the existence of such spin-dependent property has not yet been studied by means of transport coefficients.

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In the present work, we studied Shubnikov de Haas oscillations in 500 Å parabolic well in the tilted magnetic field. It is well established that the spin splitting in 2D electron gas is determined by the bare Zeeman energy and exchange-correlation term. It has been shown [3] that the spin splitting collapses when energy separation of spin-up and spin-down levels is less than the LL broadening, which determined by the single particle relaxation time  $\tau_s$ . Therefore, from measurements of the filling factor  $\nu_c$  at which the spin gap collapse occurs, it is possible to extract the total Zeeman energy. From the other side, only the bare Zeeman part of the spin gap increases as the magnetic field is tilted. It allows to separate the bare Zeeman part and exchange term of the Zeeman energy. By investigating the variation of  $\nu_c$  in tilted field we deduced the bare g-factor as a function of the external electric field.

## 2. Experimental results

The samples were made from  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  parabolic quantum wells grown by molecular beam epitaxy. It included a 500, 750 and 1000 Å-wide parabolic  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  wells with  $x$  varying between 0 and 0.20, bounded by undoped  $\text{Al}_y\text{Ga}_{1-y}\text{As}$  spacer layers with  $\delta$ -Si doping on two sides [4]. The mobility of the electrons in our 500 Å wide well was  $600 \times 10^3 \text{ cm}^2/\text{Vs}$  and the electron density  $4.4 \times 10^{11} \text{ cm}^{-2}$ . The characteristic bulk density is given by equation  $n_+ = \Omega_0^2 m^* \varepsilon / 4\pi e^2$ , where the parameter  $\Omega_0$  is associated to the parabolic variation of the potential in the well along the growth direction,  $V(z) = \frac{1}{2} m^* \Omega_0^2 z^2$ . The effective thickness of the electronic slab can be obtained from equation  $W_{\text{eff}} = n_s / n_+$ . For the  $W = 500 \text{ Å}$  wide well, we calculate  $W_{\text{eff}} = 80 \text{ Å} \ll W$ , where  $W$  is the geometric width of the well. In this case, the density profile is sharply peaked. In the presence of an electric field the minimum of the confining potential is displaced with the center of the parabolic well, whereas the shape of the parabolic well and implicitly of the envelope of the wave function are conserved. This particular property of the partially filled parabolic well makes it suitable for the practical realization of the electronic devices based on the manipulation of the g-factor. Fig. 1 shows self-consistent calculations of the potential and the electron density profile across the sample in the absence and in the presence of the external electric field. The displacement of the electronic wave function with an applied electric field away from the center results to the strong modification of the average g-factor. Fig. 2 shows the variation of the g-factor with external electric field calculated by Eq. (1).

It is worth noting that the bulk Fermi energy in our system decreases with the width as  $E_F = \hbar^2 (3\pi^2 n_+)^{2/3} / (2mW^{4/3})$  and does not depend on the electron sheet density. Since the characteristic energy of the square well  $E_0 = (2\pi)^2 \hbar^2 / (8mW^2)$  decreases with the width more rapidly than the Fermi energy, we have 1, 2, and two subbands for 500, 750, and 1000 Å parabolic well, consequently. The test samples were Hall bars with the

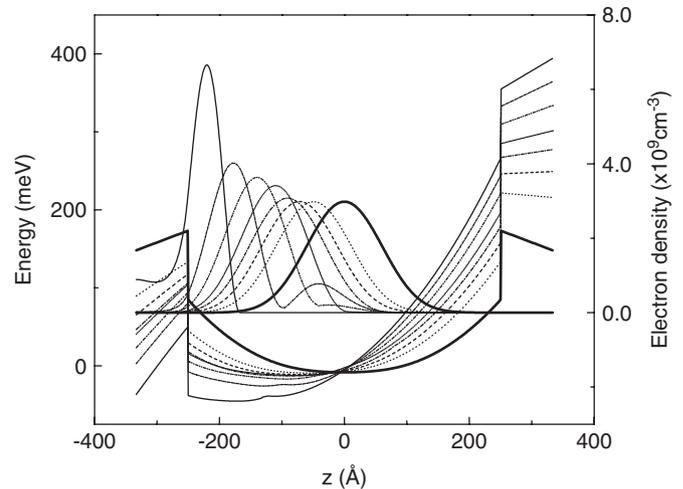


Fig. 1. Calculated total potential and electron density for a 500 Å parabolic well for different electric fields ( $\times 10^5 \text{ V/cm}$ : 0.0 (thick line), 0.05 (dots), 0.1 (dashes), 0.15 (dot-dash), 0.2 (short dot), 0.3 (dash-dot-dot), 0.4 (short dash-dot), 0.55 (thin line)).

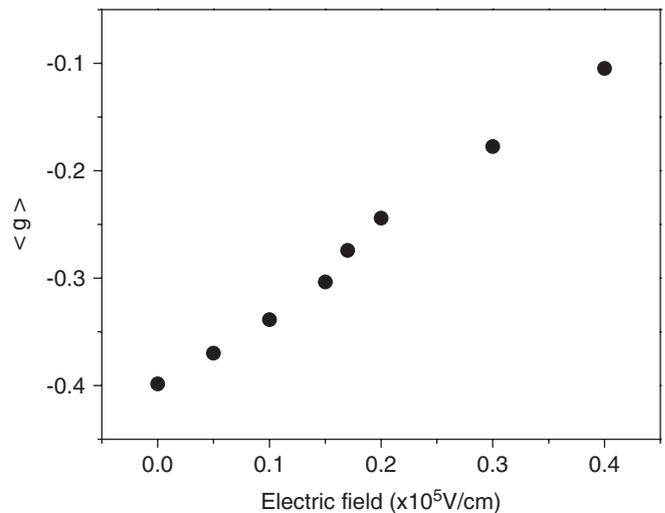


Fig. 2. Average g-factor of a 500 Å parabolic well as a function of the external electric field.

distance between the voltage probes  $L = 500 \mu\text{m}$  and the width of the bar  $d = 200 \mu\text{m}$ . Four-terminal resistance  $R_{xx}$  and Hall  $R_{xy}$  measurements were made down to 50 mK in a magnetic field up to 15 T. The sample was immersed in a mixing chamber of a top-loading dilution refrigerator. The measurements were performed with an AC current not exceeding  $10^{-7} \text{ A}$ . We measured the magnetoresistance at different angles  $\theta$  between the field and normal to the parabolic well plane, rotating our sample in situ. Below, we focus on the results obtained in 500 Å parabolic well. We also observe the variation of the g-factor with gate voltage in 750 and 1000 Å-wide wells, although the results require more complicated analysis, because these structures have two subbands occupied.

Fig. 3 shows the magnetoresistance of a 500 Å parabolic well as a function of magnetic field for different gate

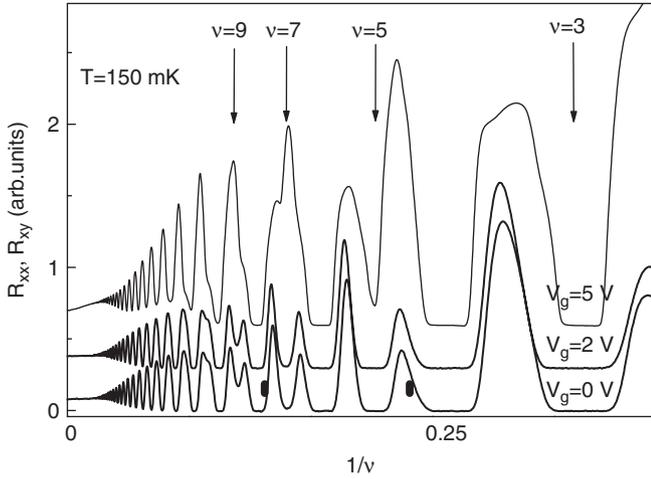


Fig. 3. The magnetoresistance of a 500 Å parabolic well as a function of magnetic field for different gate voltages at  $T = 150$  mK. Arrows show the minima in  $R_{xx}$  corresponding to the spin splitting.

voltages. We may see that the spin splitting minima are fully resolved at filling factors  $\nu = 3, 5$  and  $7$  at zero gate voltage, however, becomes partially resolved at  $\nu = 5$  and  $7$ , when external voltage is applied. Note that the amplitude of the SdH oscillations at low field is not changed with voltage, therefore the collapse of the spin splitting is not due to the increase of the level broadening. We also observe 10% increase of the electron density at  $V_g = +5$  V. Since the minima are shifted to the higher field, naively, it is expected that the spin gap will be more open. Fig. 3 shows the opposite behavior. However, we show below that the collapse of the spin occurs mostly due to the decrease of the exchange energy. It has been shown [3,5] that the spin splitting collapses when the energy separation of spin-up and spin-down levels is less than the LL broadening, which is determined by the single particle relaxation time  $\tau_s$ . Therefore, from measurements of the filling factor  $\nu_c$  at which the spin gap collapse occurs, it is possible to deduce the total Zeeman energy. It is worth noting that the spin-splitting maxima of the resistance is converging from a spacing  $\delta\nu = |\nu_\uparrow - \nu_\downarrow| = 1$  at high field to  $\delta\nu = 0$  at low field in the finite interval of  $B$ , and critical filling factor  $\nu_c$  is not very well defined. In Ref. [3]  $\nu_c$  is taken, where  $\delta\nu = 0.5$  at  $T = 0$ . Since the experimental results were done at finite temperature we define  $\nu_c$  at critical field when the depth of the minimum is less than 10% of the peak height, since the maxima start to converge rapidly for this value, as  $\delta\nu$  collapses, and it is difficult to measure  $\delta\nu < 0.5$  reliably, as a peak has a rather flat top.

As we already mentioned above, the spin splitting in 2D electron gas is determined by the bare Zeeman energy and exchange-correlation term:

$$\Delta_{\text{spin}} = g^* \mu_B B = g_0 \mu_B B + E_{\text{ex}}. \quad (2)$$

The bare Zeeman splitting is found to be 6–10 times smaller than the exchange-correlation energy. The critical filling factor can be obtained from the point where  $\Delta_{\text{spin}}$  collapses.

In Ref. [3] it has been predicted that the exchange term is destroyed by disorder at a critical filling factor, when

$$g^* \mu_B B = \hbar / \tau_s = E_s. \quad (3)$$

Note that the bare Zeeman energy will remain at this point, however, it is much smaller than the level broadening, therefore  $\Delta_{\text{spin}}$  collapses. It is worth noting that the bare Zeeman splitting depends on the total magnetic field, whereas the exchange-correlation energy depends on the perpendicular component of the magnetic field.

In the tilted magnetic field we should write [5]

$$\Delta_{\text{spin}} = g^* \mu_B B = g_0 \mu_B B + \alpha \hbar \frac{eB \cos \Theta}{m}, \quad (4)$$

since the exchange energy is given by  $E_{\text{ex}} = \alpha \hbar \omega_c$ , where  $\omega_c = eB/mc$  is the cyclotron energy and parameter  $\alpha$  can be extracted from the experiment. From Eq. (3) we estimate  $\alpha \approx 0.16$  which is close to the value of  $\alpha = 0.2$ , which was obtained in Ref. [5]. Rearranging Eq. (3) in terms of the cyclotron energy at the point, when the spin splitting collapses, we obtain for dimensionless energy

$$E_{\nu_c}(\theta) = E_s \frac{1}{\hbar \omega_c} \left( \frac{m_0}{m} \right) = \left( \frac{g_0}{2 \cos \Theta} + \alpha \frac{m_0}{m} \right). \quad (5)$$

Now, we proceed to the experimental results in the tilted field. Fig. 4 shows the magnetoresistance traces for different tilt angle for  $V_g = 0.0$  V. Arrows show the resistance maxima with partially resolved spin splitting. Note that the spin split minima are deeper and critical filling factor at which spin gap collapses increases at higher tilt angle. We attribute such behavior to the additional parallel component of the magnetic field at higher tilt angle, which results to the opening of the spin gap by the increasing of the bare Zeeman energy contribution. From the magnetoresistance traces shown in Fig. 4, we obtain the critical magnetic field at which spin splitting collapses and,

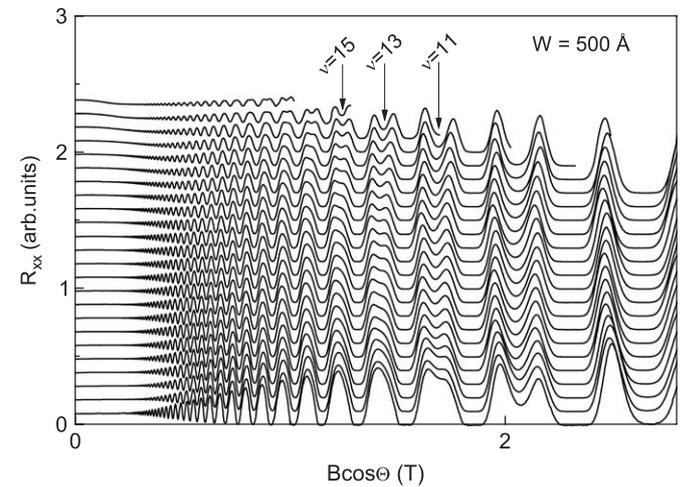


Fig. 4. The magnetoresistance of a 500 Å parabolic well as a function of magnetic field at  $T = 150$  mK for different tilt angles (from the bottom trace to the top angle  $\Theta$  varies from  $0^\circ$  to  $85.1^\circ$ ),  $V_g = 0$  V. Arrows show the minima in  $R_{xx}$  corresponding to the critical filling factors, when spin gap collapses.

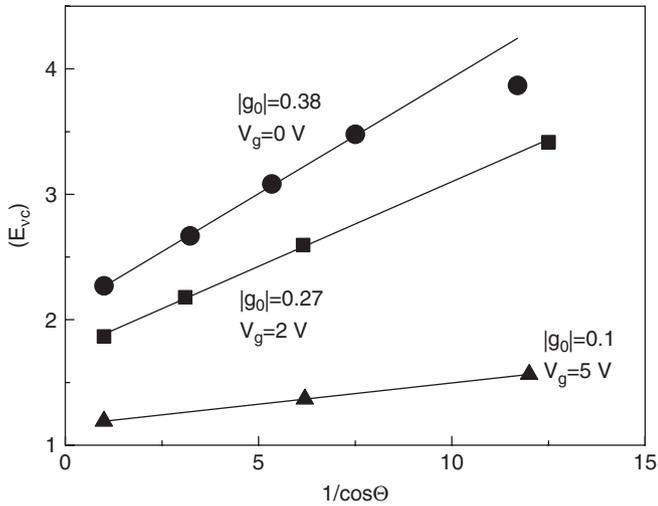


Fig. 5. Variation of the dimensionless energy  $E_{vc}$  corresponding to the critical magnetic field at which spin gap collapses as a function of the tilt angle for different voltages. Solid lines are drawn from the prediction of Eq. (5).

consequently, the dimensionless energy  $E_{vc}$  as a function of the tilt angle. Fig. 5 shows  $E_{vc}$  versus  $1/\cos\theta$  for different gate voltages. From comparison with Eq. (5) we extract the bare g-factor. We may see that for zero gate voltage

g-factor is in good agreement with bulk value of 0.44. As expected, the slope of the line in Fig. 5 decreases with gate voltages, which corresponds to the decrease of the bare g-factor. Note that we are not able to change the sign of the g-factor in our samples. For this aim the parabolic  $\text{Al}_x\text{Ga}_{x-1}\text{As}$  wells with  $x = 0.06-0.1$  in the center of the well are more appropriated. Indeed, we attempt to grow such structures, however, they have much lower mobility due to the strong alloy scattering. Further progress in the growing of such material is necessary.

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