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Gate-controlled electron spin resonance in GaAs/$Al_xGa_{1-x}As$ heterostructures

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The electron spin resonance (ESR) of two-dimensional electrons is investigated in a gated GaAs/AlGaAs heterostructure. We found that the ESR resonance frequency can be tuned by means of a gate voltage. The front and back gates of the heterostructure produce opposite *g*-factor shift, suggesting that electron *g* factor is being electrostatically controlled by shifting the equilibrium position of the electron wave function from one epitaxial layer to another with different *g* factors.

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Isolated electron spins in low-temperature semiconductors are now recognized[1] to have considerable potential for storing and manipulating quantum information. One of the great advantages of a spin in a semiconductor is that it can be embedded into a transistor structure, and it can thereby lend itself to large-scale integration of a quantum information processor. One essential element for spin-based quantum information processing is to be able to individually address the spins, or qubits. In an innovative paper, Kane[2] proposed that the nuclear spin of a donor atom in Si can be manipulated and controlled, via the hyperfine interaction between the electron and nucleus, by a transistor gate. We have recently suggested[3] that this gate-controlled spin concept should be implemented directly on electron spins, since electronic band structure directly accesses the electron *g* factor, whose matrix elements actually resemble those for effective mass. In this case, the *g* factor of an individual electron is tuned by a local gate electrode with respect to the frequency of a constant microwave field, to bring the spin in and out of the resonance.

There is a large body of work[4] on the influence of composition and quantum well structure on *g* factors. Adjacent semiconductor heterostructure layers can have very different electron *g* factors. For example, Si-Ge alloys change from $g=1.99$ to $g=0.82$ over a narrow range of alloy composition. Likewise GaAs has $g=-0.44$, while Al-Ga-As has $g=+0.4$. Thus, the field-induced shifting of the electron wave function between such layers can produce large *g*-factor changes, allowing direct *g*-factor tuning by means of a gate voltage.

In this paper, we report our observations of gate-voltage tuned ESR in a two-dimensional electron system. We demonstrate that the electrostatic field of a gate can effectively adjust the weighting of the electron wave function between heterostructure layers of different composition producing a large *g*-factor change.

The sample used for these experiments is a modulation doped GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructure. The layers were grown by molecular-beam epitaxy on the $\langle 001\rangle$ face of a GaAs wafer. A 40-nm undoped $Al_{0.3}Ga_{0.7}As$ spacer layer was used to separate the Si donor layer ($n=1\times10^{18}/\mathrm{cm}^3$, 50-nm thick) from the two-dimensional electron gas (2DEG) formed between the spacer and a 500-nm GaAs buffer layer. NiCr gates were evaporated both on the front and back of the sample. Biasing the gate allowed us to control both the electrical field perpendicular to the 2DEG plane and the density of the 2DEG. To ensure good electrical insulation between the gate and the 2DEG another undoped $Al_{0.3}Ga_{0.7}As$ layer (100-nm) was included on top of the doped $Al_{0.3}Ga_{0.7}As$ layer, followed by a 10-nm GaAs cap layer. Standard photolithography patterned a large area channel of width 150 μm and length 450 μm. Indium was diffused into the channel to form Ohmic contacts. The mobility of the unbiased device at liquid-helium temperature was 800 000 $\mathrm{cm}^2/\mathrm{V\,sec}$.

To monitor electron spin resonance in bulk semiconductor systems, it is customary to detect microwave power absorption at spin resonance. To obtain adequate signal amplitude, about 10^{12} spins are normally required. For our structure, there are only about 10^7–10^8 electrons available in the active channel. Therefore, we have chosen to detect the ESR by monitoring the electrical resistance of the source/drain channel.

It was demonstrated as early as 1983, in pioneering work by Stein, v. Klitzing, and Weimann,[5] that the magnetoresistance of the 2DEG can be very sensitive to spin resonance, when the Fermi level is located between spin-split states of a given Landau level. Recent work[6–11] on a variety of GaAs based devices have further demonstrated that resistive detection is extremely effective for studying the magnetic resonance of electron as well as the nuclear spin.

Our experiment was carried out in a top-loading Helium 3 cryostat in a superconducting magnet. A low-loss coaxial cable was used to deliver microwave radiation (≈ 1 mW) to the sample. Figure 1 illustrates the setup for detecting the ESR signal by means of source/drain channel resistance. An ac probe current $I_{ac}=200$ nA at 720 Hz was applied from the source to the drain. Then a lock-in amplifier monitored the channel resistance R_{xx} through two additional electrical contacts along the channel. The microwave radiation, provided by a HP sweep generator was modulated at 100% with a frequency of 10.8 Hz, much lower than the probe current frequency. A second lock-in amplifier synchronous at 10.8Hz then measured the microwave induced change in resistance δR_{xx}. This double modulation technique discrimi-

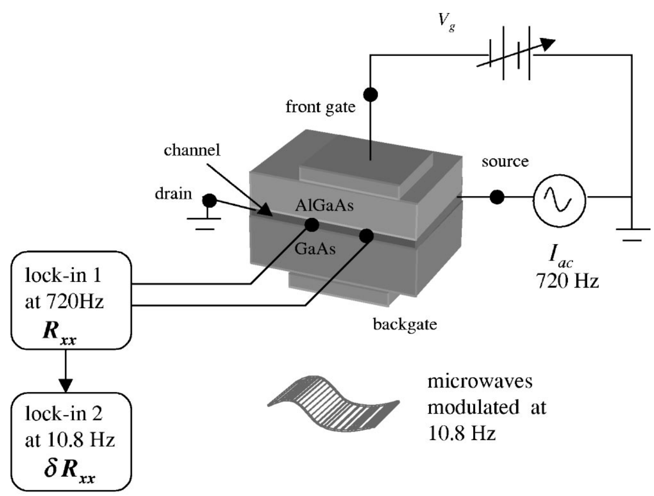

FIG. 1. Diagram of the experimental setup for monitoring electron spin resonance and for controlling the spin orientation.

nated against possible thermovoltaic or photovoltaic effects. The temperature for this experiment was chosen to be 1.2 K, although lower temperatures were also studied. At this temperature over 70% of the electron spins are already well polarized at a moderate field, about 2.5 T.

The experiment was carried out in the quantum Hall effect regime. In Fig. 2, we show the typical channel resistance ρ_{xx} versus magnetic field, and the corresponding change in channel resistance $\delta\rho_{xx}$ due to microwave radiation, all in Ohms as a function of perpendicular magnetic field on the 2DEG. The carrier density is $n \approx 1.8 \times 10^{11}/\mathrm{cm}^2$, with no dc voltage applied to the gate. The oscillations in channel resistance can be roughly understood as the successive filling of Landau levels as the magnetic field is reduced. The number of filled quantum states, the filling factor ν, is given by hn/cB where h is Planck's constant. In this terminology, there are two spin states $S_z = \pm 1/2$ for each Landau level. For example, a filling factor $\nu = 3$ indicates that both spin states of the N=0 lowest Landau level, and $S_z = +1/2$ of the next higher $N=1$ Landau level, are fully occupied by electrons as shown in the inset. The majority of features displayed in the Fig. 2(b) are not due to ESR. Their origin has been commonly identified in the literature as being due to microwave heating. However, the sharp peak at $B \approx 2.5$ T is due to the ESR, whose position depends strongly on the microwave frequency.

We have worked mostly in a narrow range of gate voltage around $V_g = +0.1$ V. At this gate voltage, the density of the 2DEG is about $1.9 \times 10^{11}/\mathrm{cm}^2$, corresponding to the $S_z = +1/2$ state of the second Landau level (i.e., $\nu = 3$, $N=1$) at a magnetic field of about 2.65 T. It is worth noting here that the ESR signal was indeed detected for several other odd filling factors (i.e., $\nu = 1$, 5, and 7). We found that the ESR signal can be detected both in channel resistance, and gate capacitance (or density of states). The change in occupation density for the $S_z = -1/2$ state at ESR confirms that there are actual spin flips in the sample. The ESR linewidth (i.e., full width at half maximum) was found to be around 70–150 G (corresponding 35–70 MHz) depending on the excitation

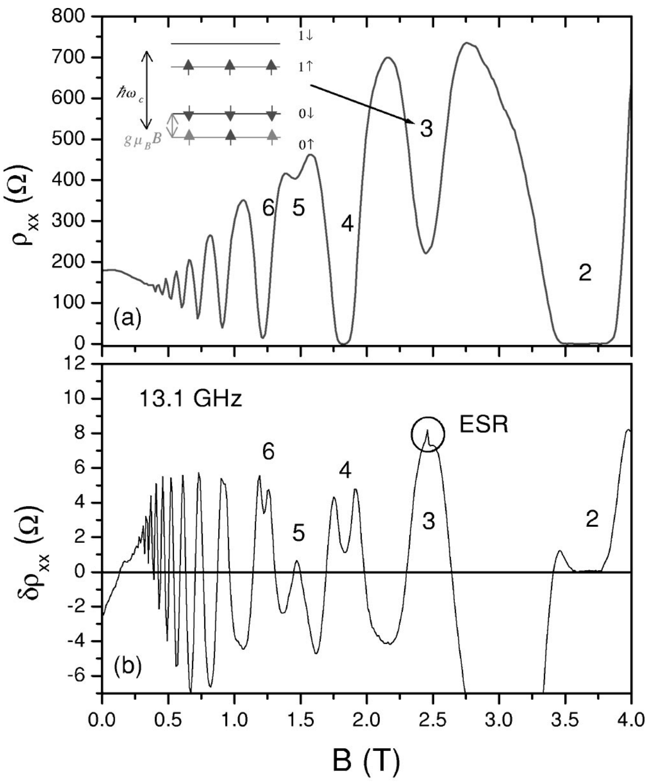

FIG. 2. (a) Typical trace of the resistivity ρ_{xx} as a function of the magnetic field. Landau level filling factors ν are indicated. Inset: energy diagram for the case of $\nu = 3$. (b) The microwave radiation induced resistivity change $\delta\rho_{xx}$. Note the ESR feature around $\nu = 3$.

power and temperature. The linewidth is known to be inhomogenously broadened by the hyperfine interactions with nuclear spins, Ga^{69}, Ga^{71}, and As^{75} all having nonzero spin angular momentum, $I = 3/2$. We found this linewidth is power dependent. Due to the fast rate of dynamic nuclear polarization by cross relaxation, the line can be much broader at higher excitation powers.

Figure 2(b) shows that the electron spin state can control the channel resistance. Now we will show that the gate can in turn control the spin. In this part of the experiment, we varied the bias voltage around filling factor $\nu = 3$ from 0.1 to 0.16 V. The ESR signal is best detected at exactly $\nu = 3$, and the ESR signal strength diminishes quickly on either side away from full filling. The gate voltage variation of 0.06 V introduced a 12% density (or filling factor) change, about the limit of our sensitive range. Even within this rather small gate voltage range, we have been able to monitor the shift in ESR spectrum.

Figure 3(a) shows a sequence of ESR spectra at different gate voltages. At a fixed microwave frequency of 14.1 GHz, the peak position shifts clearly and progressively from 2.672 to 2.682 T as the gate voltage is increased. The experimentally measured g factor versus applied electric field E is plotted in Fig. 4. Although the variation of the g factor is only about 0.5%, that tunes over 1 linewidth, within this voltage range. In another sample from the same wafer, we have also placed a backgate on the GaAs substrate that is about 0.5

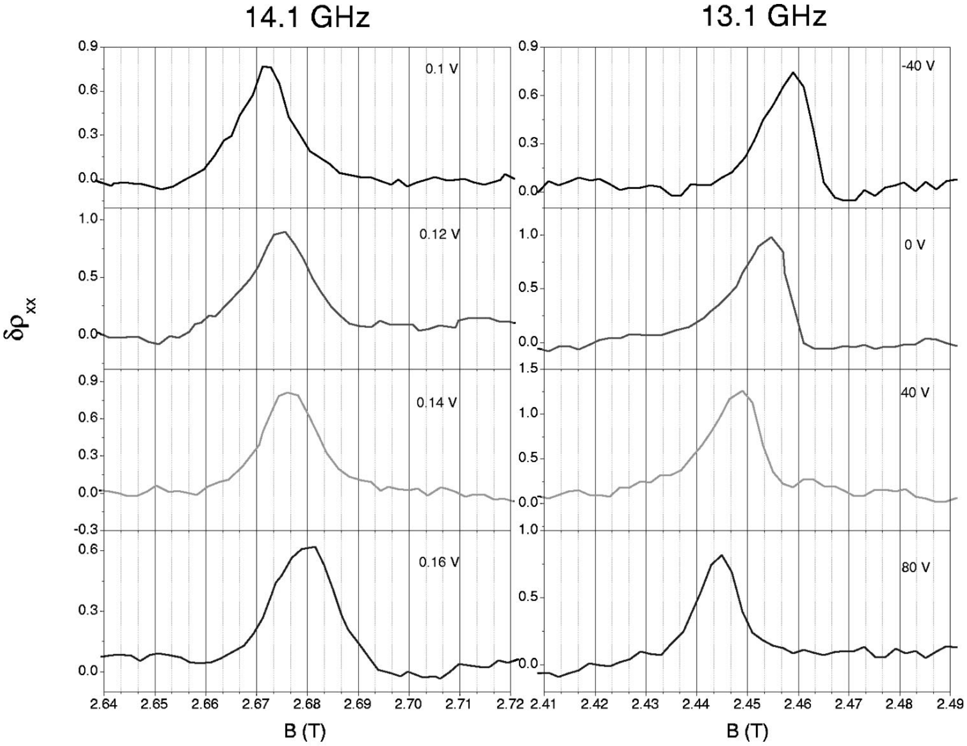

FIG. 3. Electrically detected electron spin resonance spectra at a sequence of gate voltages for (a) a front gate and (b) a back gate. For the front gate case, the resonant peak moves progressively to higher magnetic field when the amplitude of the bias gate voltage is increased. In contrast, the peak shifts towards lower field for the back gate case. (The smooth nonresonant background of the signal was subtracted for clarity.)

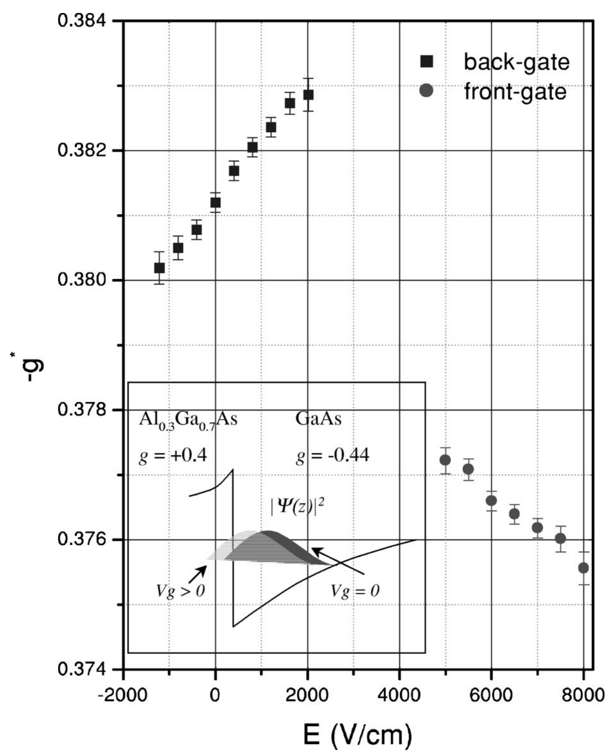

FIG. 4. Experimentally determined electronic g factor as a function of the applied electric field, for both the front and back gate. The plotted electric field is simply the applied voltage divided by insulator thickness (no attempt was made to include space charge self-consistently). Inset: The two-dimensional electrons are trapped in the ''triangle'' shaped quantum well near the interface of the GaAs and $Al_{0.3}Ga_{0.7}As$ materials. The electron wave function shifts back and forth for a positive front gate bias voltage, and for $V_g=0$.

mm away from the 2DEG. The ESR spectra for different backgate voltages is shown in Fig. 3(b). However, in contrast to the front gate case, the peak position actually shifts towards lower fields with increasing positive gate voltage. The g factor has a ''blue shift'' rather than a ''red shift'' observed for the front gate case.

Both front and backgate voltages are measured with respect to the 2DEG channel, which is grounded. Thus in both cases, a positive gate increases the Fermi energy of the 2DEG. The possibility of a 12% change of 2DEG density leading to a g-factor shift can be ruled out experimentally. The increasing positive gate voltage would increase the density of the 2DEG for *both* the front and back gate cases. In contradiction, a field shift in the opposite direction is observed for the back gate case.

It is well known that the g factor in a 2DEG system depends on magnetic field as well as Landau level index N as follows: $g(B,N)=g_0-c(N+1/2)B$, where g_0 and c are sample dependent constants. In an earlier experiment, the g factor was found to diminish continuously as magnetic field is increased.[12] This g-factor dependence was explained quantitatively by taking into account of the nonparabolicity of the bulk band structure.[13] For the nearly parabolic bulk GaAs band, the g factor is known to be $g=-0.44$. Note that this value deviates significantly from the free-electron value of $g=2.0023$ due to spin-orbit coupling. As the Fermi energy of the degenerate 2DEG increases, the energy band deviates progressively from the parabolic case, which leads to a reduction of the spin splitting. This nonparabolicity effect was indeed observed in our experiment (not shown) for large variations of B at a given Landau level. This nonparabolicity cannot, however, explain our gate-controlled observations. In the first place, the shift would be in the same direction for front and back gate cases, contrary to what is seen. In the second place, the employed range of magnetic tuning field ΔB should result in a g-factor change of only $3c\Delta B/2$ or about 0.045% (for a typical value of $c \approx 0.014\ \mathrm{T}^{-1}$) which is far less than the observed g-factor change of 0.5%. It is worth noting here, in principle, the front-gate and the back-gate can have a different influence on the shape of the triangular well. In general, a detailed theoretical calculation similar to that in Ref. 13 is required to determine the weight of the nonparabolicity in the g modulation.

The mechanism that we invoke for the opposite g-factor shift between front and back gate cases is ‘‘g-factor engineering’’ of the heterolayers.[3] In this picture for the front gate case, as the magnitude of the gate voltage is increased, the wave function of the 2DEG is redistributed towards the $Al_{0.3}Ga_{0.7}As$ side, as illustrated graphically in the inset of Fig. 4. Since the g factor of $Al_{0.3}Ga_{0.7}As$ is about $g=+0.4$, the effective electronic g factor, is consequently reduced. Since the energy barrier against wave-function redistribution on the $Al_{0.3}Ga_{0.7}As$ side is about 0.2 eV, the change in effective g factor is expected to be relatively modest, as observed. For a back gate, an increasing gate voltage would enhance the weight of the wave function on the GaAs side, which increases the g factor. This wave-function redistribution induced ESR is very different in origin, and is much greater than those due to g-factor anisotropy in different crystal directions, that have previously observed.[14]

To verify this wave-function model quantitatively, we have performed a self-consistent calculation (i.e., solving the Schodinger and the Poission equations of the band structure simultaneously) by using commercial semiconductor modeling software.[15] The wave-function distribution was evaluated for different front-gate bias voltages. Our calculation has shown that about 3% the wave function penetrates into the $Al_{0.3}Ga_{0.7}As$ barrier. The g factor was then determined by a weighted average over the two regions: $g=\int|\psi(z)|^2 g(z)dz$. The penetration portion changes about 0.3% of the wave function for a bias voltage difference of 60 mV which leads to a g-factor shift of about 0.7%. This simulation is in surprisingly good agreement with our experimental observations. Although, this self-consistent calculation is intuitively informative, it is no substitute for a full band-structure calculation. Spin-orbit coupling, isotropic and anisotopic k-dependent contributions, etc., would be required to obtain good quantitative theoretical agreement. For the application this effect to spin-based quantum information processing, one requires the control of individual electrons, a far more challenging task. However, we believe the demonstrated gate controlled ESR should be, in principle, applicable to the single spin case.

In conclusion, we have demonstrated in a GaAs/AlGaAs heterostructure the gate can control the electron spin by tuning it in and out of ESR resonance frequency. Both red-shift and blue-shift of the ESR frequency were observed for positive front gate and positive back gate, respectively, proving that Fermi level changes cannot account for the g shift. The observations suggest that the gate controlled ESR is due to the tuning of the electron wave function probability weight between heterostructure layers of different compositional g factor.

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