Electron Spin Resonance on a Two-Dimensional Electron Gas in a Single AlAs Quantum Well

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Direct electron spin resonance (ESR) on a high mobility two-dimensional electron gas in a single AlAs quantum well reveals an electronic g factor of 1.991 at 9.35 GHz and 1.989 at 34 GHz with a minimum linewidth of 7 G. The ESR amplitude and its temperature dependence suggest that the signal originates from the effective magnetic field caused by the spin-orbit interaction and a modulation of the electron wave vector caused by the microwave electric field. This contrasts markedly with conventional ESR that detects through the microwave magnetic field.

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Electron spin resonance (ESR) has long been used to extract g factors and g-factor anisotropies of different kinds of solids and molecules, thus providing experimental verification for band structure calculations in solids and structure calculations in molecules. Additionally, spin-lattice relaxation times (T_1) and spin-spin dephasing times (T_2) can be determined [1]. More recently, ESR has successfully been employed to study g factors and spin relaxation of 2D electrons in Si/SiC [2] and Si/SiGe [3] structures. ESR on 2D systems also provided information about 2D electron-donor exchange tunneling [4] and on potential fluctuations caused by remote doping [5,6], without the need for Ohmic contacts to the samples. Moreover, from the dependence of the g-factor anisotropy on Fermi wave vector and from that of the g factor on angle between microwave field and static magnetic field, recently the (tiny) Bychkov-Rashba spin-orbit interaction of 2D electrons in Si/SiGe samples could be determined [7,8]. In this Letter, we show that in high mobility 2D samples this spin-orbit interaction allows one to resonantly manipulate the electron spin by means of gigahertz *electric* fields.

Direct ESR on a two-dimensional electron gas (2DEG) has proved difficult because of the typically small number of spins in the 2DEG. So far it has been restricted to Si (either in Si/SiC or in Si/SiGe samples) because of its favorable physical properties. As the sensitivity of ESR is proportional to the inverse of the linewidth squared, narrow linewidths are a prerequisite. In Si, linewidths down to 3 μT are observed [8], as little T_1 broadening occurs. This is because Si has a rather small spin-orbit (SO) interaction. Also it has only one isotope with nuclear spin (^{29}Si), which additionally has only a small natural abundance (4.7%). This contrasts markedly to the III-V semiconductors where there are many isotopes with nuclear spin (^{69}Ga, ^{71}Ga, ^{27}Al, ^{75}As, ^{115}In, ^{31}P, etc.) with large natural abundance, many of which have a strong SO coupling. This leads to considerable line broadening and, at low temperatures, where ESR usually has the best sensitivity, to large hyperfine fields that vary slowly with time. Consequently, direct ESR has never been demonstrated on 2D electrons in III-V semiconductors.

Here, we present the first direct ESR on a 2DEG in a III-V semiconductor. We study ESR of high mobility 2D electrons in a single AlAs quantum well. At 9.35 GHz and at 34 GHz g factors of 1.991 and 1.989 were determined, respectively. By rotating the sample in the cavity, we demonstrate that our ESR originates from the microwave *electric* field (E_1 field) and not from the microwave magnetic field (B_1 field). For small power (P) of the E_1 field, the ESR follows a $P^{0.5}$ law, but, for larger powers, the exponent increases to $\sim$1. The temperature dependence of the ESR is much stronger than the 2D magnetization expected for such a system [2]. Our observations can be explained by assuming that the spin transitions occur through the effective magnetic field caused by SO interaction and the modulation of the electron wave vector around k_F induced by the microwave E_1 field.

Our sample is a 2×4 mm^2 piece of a GaAs wafer that contains a 15 nm wide AlAs quantum well (QW) flanked by $Al_{0.45}Ga_{0.55}As$ barriers. It is volume doped with Si (4×10^{18} cm^{-3}) over 30 nm with spacers of 40 and 30 nm below and above the QW. Transport measurements on samples from the same wafer reveal that the 2D electrons occupy both in-plane X valleys [9]. The carrier density is 2.5×10^{15} m^{-2} and at 4 K the mobility is 12.5 m^2/V s, which compares well with the best results found in literature [10]. The GaAs substrate of our sample was thinned to $\approx$80 μm to minimize dielectric disturbances of the cavity modes ($\varepsilon_{GaAs} = 13.1$).

In an ESR experiment, the absorption of microwaves by magnetic dipole transitions in a sample is measured. The (static) magnetic field (B_0) is swept at a fixed microwave frequency (f) and the reflected microwave power (P) is detected. A feature is observed at the resonant condition, given by $g\mu_B B_0 = hf$, with g the g factor of the material. In our experiment (as in most others), B_0 is slightly modulated and ESR ($\propto \sqrt{P}$) is lock-in detected.

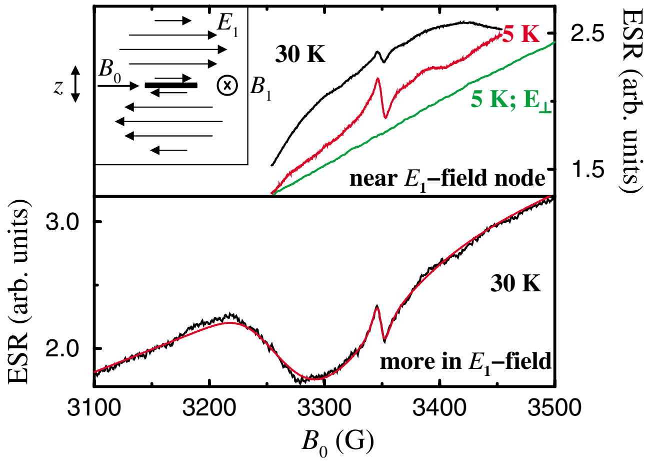

FIG. 1 (color online). Top panel: ESR at 30 and 5 K measured at 9.35 GHz and 20 mW with the sample near a node in the E_1 field. The second trace at 5 K demonstrates the absence of ESR when the QW is oriented perpendicular to the E_1 field. The inset shows the orientation of the QW (solid black bar) with respect to the static and microwave fields for the top two traces. Bottom panel: ESR with the sample more in the E_1 field, i.e., shifted by 1 mm ($\approx 1/30\ \lambda$) in the z direction compared to the inset.

Figure 1 plots the ESR vs magnetic field at 9.35 GHz (X band), measured with a Bruker spectrometer with automatic frequency control (AFC) in a rectangular cavity (TE_{102} mode, Bruker ER410ST). Data in the top panel are measured with the sample positioned near the node in the E_1 field. The top trace was measured at 30 K with the QW parallel to the B_1 and E_1 fields and clearly shows a feature near 3349 G. Upon decreasing the temperature to 5 K (middle trace), the feature grows in amplitude, but stays at the same position. The data at 5 K are reasonably well fitted by the derivate of a single Lorentzian. Because of the AFC, only the absorptive part of the signal can be measured. The line has a width of 7 G and is centered around 3349 G, which yields a g factor of 1.991. We note that for temperatures above ~10 K a single Lorentzian gives a less satisfactory fit to the data, suggesting that there is a (small) additional contribution to the signal [11].

The observation of a line with a width of 7 G and a signal-to-noise ratio of 10 represents a puzzle, as the sensitivity of the cavity at a power of 20 mW is only 3×10^{10} spins for a linewidth of 1 G. As our sample contains only 2×10^{10} 2D electrons, for a linewidth of 7 G the ESR should be 74 times smaller than the noise level. We note that the electrons at the Si dopants in the barrier material ($Al_{0.45}Ga_{0.55}As$) have a very different g factor (+0.6 [13]) and cannot account for the signal. Nonetheless, to verify that the signal originates from the 2D system, ESR was also measured with the QW perpendicular to the E_1 field (bottom curve in the top panel of Fig. 1). In such orientation no ESR was observed, proving that the signal does not originate from 3D (doping) layers. Moreover, it further proves that the measured ESR does not originate from the B_1 field as is normally the case [2–8,12] (note that the B_1 field is still parallel to the QW and perpendicular to B_0), but surprisingly that it is caused by an in-plane E_1 field.

Figure 1, bottom panel, plots the ESR at 30 K with the sample placed more in the E_1 field in order to enhance the signal. Indeed, the ESR feature can be more clearly seen, but it is superimposed on a rather large, broad, and very asymmetric background. This background is well fitted (solid line) with a statistic extreme value function [$I = \exp[1 - z - \exp(-z)]$; $z = (x - x_c)/w$ with x_c the center position (3302 G) and w the width of the distribution (48 G)]. Such a function is commonly used in nonlinear physics to describe the distribution of first moments of underlying distributions [14], but at present its physical meaning is unclear. Naively thinking, the extent of the signal from 3200 to 3450 G implies that a whole spread of g factors is contributing, possibly originating from electrons that are accelerated high up in the conduction band.

Figure 2 plots the ESR at 33.94 GHz (Q band) measured in an oversized, home-built Fabry-Perot cavity without AFC. In this cavity, B_0 is perpendicular to both the E_1 and B_1 fields. The sample is mounted perpendicular to B_0 and close to the E_1 field maximum. Top traces plot the ESR of the sample and a Li:LiF marker (solid line), and that of the Li:LiF marker only (dashed line) at 30 K. The marker was included to determine the precise g factor of the 2D electrons. It further allows us to determine the phase of the ESR of the 2D electrons. The bottom trace (solid line) plots the ESR at 22 K. In all ESR traces with the sample in the cavity, a clear feature at 12 190 G appears, which corresponds to a g factor of 1.989. In the temperature range studied (5–35 K), this g factor is constant. The most striking feature, however, is that the ESR of the 2D electrons is mostly dispersive, whereas that of the marker is (as it should be) almost completely absorptive. The ESR of the

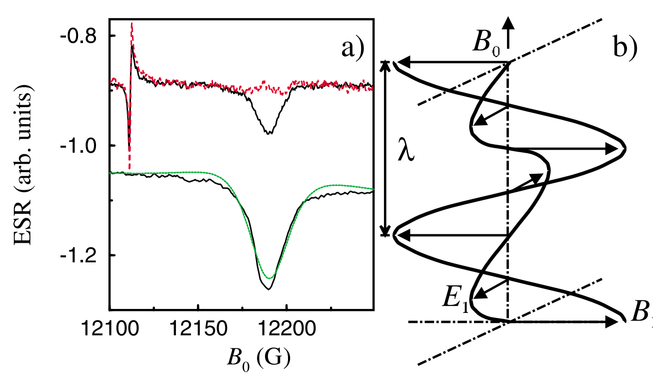

FIG. 2 (color online). (a) Top: ESR at 30 K measured at 33.94 GHz and 10 mW with the sample and a Li:LiF marker ($g = 2.002\,293$) present (solid line) and with Li:LiF only (dashed line). Bottom: ESR at 22 K (solid line) with a dispersive single Lorentzian fit (dotted line). (b) Orientation of the B_0, B_1, and E_1 fields. The QW is perpendicular to B_0 and $\approx 1/4\ \lambda$ above the bottom of the cavity (near the E_1 field maximum).

2D electrons is thus significantly phase shifted compared to the normal B_1 field induced transitions in the marker. The dotted line is a single dispersive Lorentzian fit and describes the largest part of the ESR signal. Just as for 2D electrons in Si [12], there is a small additional contribution to the ESR signal [11].

Before presenting the temperature and power dependencies of the ESR, we first comment upon its possible origin. From the absence of any ESR when the QW is perpendicular to the E_1 field, we conclude that it arises from an in-plane E_1 field. This E_1 field can in principle cause ESR in two ways. First, it accelerates the high mobility electrons, thus inducing currents in the sample, which in turn generate a magnetic field (B_2). The component of B_2 perpendicular to the B_0 field can cause transitions, resulting in an ESR signal. In X band with $P = 20$ mW, $|E_1|_{\max}$ is 240 V/m. The measured sheet conductivity of the 2DEG at 4 K is 5.0×10^{-3} (Ω^{-1} m^{-1}). If we mimic the QW as an infinite thin metal plate, then the B_2 field ($\equiv (1/2)\mu_0 j$) is 8 mG, more than 1 order of magnitude *lower* than the B_1 field (0.2 G).

Second, we note that, for high enough mobility samples, the E_1 field accelerates/decelerates the electrons periodically in each half of the microwave cycle. This leads to a modulation of the electron wave vector, which in materials with SO interaction will cause an effective magnetic field that acts on the electron spins only. In our X band cavity only the effective magnetic field due to the Bychkov-Rashba [15,16] part of the SO interaction is perpendicular to B_0 and can cause transitions. For the orientation in Q band, also the Dresselhaus [17] part contributes to the effective magnetic field. Because the AlAs crystal structure lacks inversion symmetry and because the QW structure is not symmetric in the growth direction, both parts of the SO interaction should be present. A necessary condition for the appearance of a wave vector modulation is that the scattering time of the electrons (τ) is comparable to or larger than the inverse microwave frequency so that at least part of the electrons follow a cycle of the E_1 field without being scattered. This is indeed the case in our samples; from the mobility at 4 K (12.5 m^2/V s), using an effective mass of $0.46 m_e$, we obtain a scattering time of 33 ps, which is comparable to the 100 ps (X band) or 30 ps (Q band) inverse microwave frequency.

We now estimate the magnitude of the effective magnetic field. The Bychkov-Rashba SO interaction for a sample that is not symmetric in the growth direction (z) can be written as $\mathcal{H}_{\mathrm{BR}} = \alpha_{\mathrm{BR}}(\mathbf{k} \times \sigma) \cdot \mathbf{e}_z$ [15,16], with α_{BR} the Bychkov-Rashba constant of the material, $\mathbf{k}$ the electron wave vector, and σ the Pauli spin matrices. It is evident that the spin and the orbital motion are coupled. To translate the energy into an effective magnetic field, we divide by $(1/2) g \mu_B$. This gives an effective field of $\mathbf{B}_{\mathrm{BR}} = (2\alpha_{\mathrm{BR}}/g\mu_B)\mathbf{k} \times \mathbf{e}_z$. For high enough mobilities, the E_1 field modulates the wave vector of the electrons, i.e., $\mathbf{k} = \mathbf{k}_F + \Delta\mathbf{k}$. For X band, assuming an infinite scattering time, $\Delta\mathbf{k}$ becomes $e|E_1|/(hf)$. Since the scattering time is not infinite but somewhat smaller than the inverse microwave frequency, and to estimate $\Delta\mathbf{k}$ in Q band and to determine the phase of the effective magnetic field with respect to the B_1 field, we performed a Monte Carlo simulation, assuming an isotropic effective mass and an energy independent scattering time taken from transport experiments. We integrate the force on the electron [$-eE_1$ for X band and $-e(E_1 + v \times B_0)$ for Q band], and after a fixed time of flight ($\ll \tau$) we determine whether the electron scatters or not. If it scatters, it restarts at the Fermi energy. In X band with $P = 20$ mW, $|E_1|_{\max}$ is $\sim$240 V/m and $\Delta\mathbf{k}$ becomes 2×10^6 m^{-1}. It is phase delayed by 60°. Note that in X band because of the AFC only the absorptive part of the ESR is measured. For Q band with $P = 10$ mW, $|E_1|_{\max}$ is $\sim$200 V/m and $\Delta\mathbf{k}$ becomes 0.5×10^5 m^{-1}. Because of the $v \times B_0$ term, it is much smaller and its phase is $-70°$ with respect to the B_1 field. The ESR of the 2D electrons should thus be almost completely dispersive, which is indeed observed in the experiment (see Fig. 2).

To estimate $\mathbf{B}_{\mathrm{BR}}$ we have to estimate α_{BR} for AlAs, as it is not known. We note, however, that the deviation from the free electron g factor is caused by SO interaction and that this deviation for AlAs is nearly 8 times larger than that for Si [7]. For our estimate, we assume α_{BR} to scale with the SO interaction, and use the measured α_{BR} of Si (5.5×10^{-15} eV m) [7] to calculate $\mathbf{B}_{\mathrm{BR}}$. This effective magnetic field then becomes 14 G in X band, almost 2 orders of magnitude larger than the B_1 field (0.2 G). We note that the estimated B_{BR} is twice as large as the smallest linewidth measured, but, given the crudeness of the model, it agrees surprisingly well with the necessary field strength needed to detect ESR of 2×10^{10} spins. In Q band both the Dresselhaus and the Bychkov-Rashba interactions contribute to the effective field and, although the estimated $\Delta\mathbf{k}$ is much smaller, the Dresselhaus part (that in III-V semiconductors contains an additional $\mathbf{k}^3$ term next to the linear term) could still cause a sizable effective magnetic field.

Since the scattering time is somewhat shorter than the inverse microwave frequency, only part of the electrons will be able to follow the E_1 field. As the temperature is increased, this part will decrease since the scattering time decreases. Consequently, the temperature dependence should be stronger than the 2D magnetization. This is indeed the case. Figure 3 plots the ESR intensity vs temperature for both X band (■) and Q band (▲). The solid line is the 2D magnetization [2] for our AlAs 2DEG (E_F = 7.8 K). This temperature dependence is clearly much too weak to describe the data. This is not surprising since the measured scattering time is also a rather strong function of temperature (dotted line) and, according to the above, the ESR should represent both the scattering time and the 2D magnetization.

To determine the spin dephasing time from the saturation at higher microwave power, we conducted power dependent measurements. Figure 4 plots the ESR intensity

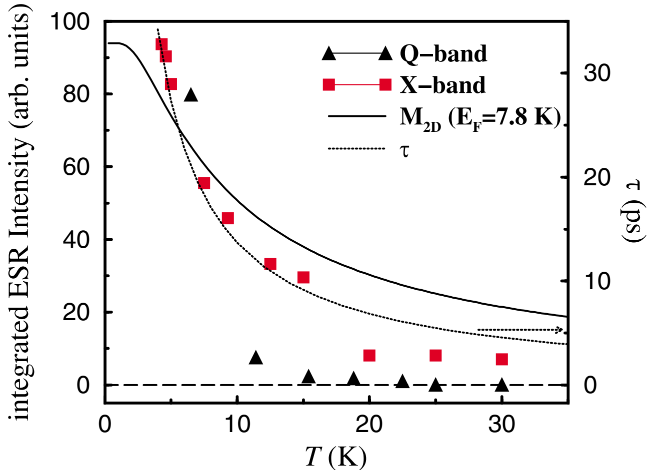

FIG. 3 (color online). Integrated ESR intensity in Q band (▲) and X band (■) vs temperature; $P = 20$ mW. Solid line: magnetization of a 2DEG with a density of 2.5×10^{15} m^{-2} with two valleys occupied and a mass of $0.46m_e$. ($E_F = 7.8$ K). Dotted line: the scattering time derived from the measured mobility.

vs P in Q band. The squares were taken with the sample positioned close to a node in the E_1 field and follow a $\sqrt{P}$ dependence, commonly observed in ESR. It implies that the ESR intensity is proportional to the (in our case, effective) microwave magnetic field. When the sample is positioned more in the E_1 field (▲), the power dependence changes significantly. For low P, the ESR intensity is still approximately proportional to $\sqrt{P}$, but, for higher P, instead of saturating, it becomes approximately linear in P.

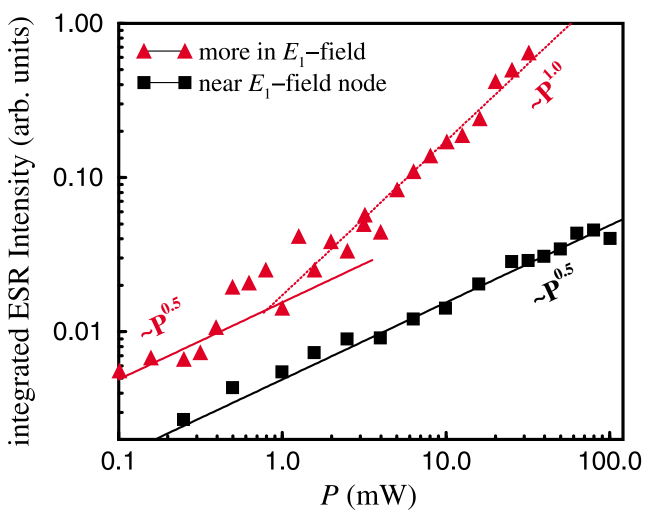

FIG. 4 (color online). Power dependence of the integrated ESR intensity in Q band at 28 K. Squares are measured with the sample close to a node in the E_1 field and show an approximate $\sqrt{P}$ dependence (solid line); triangles are measured with the sample more in the E_1 field. For high P, the ESR is approximately linear in P (dotted line).

At high P, we envision that the microwaves cause so many spin transitions that the 2D magnetization is forced out of thermal equilibrium. If the conductivity of the 2D electrons (σ_{2D}) for spin-up differs from that for spin-down, then the power dissipated by the 2D electrons will change at the resonance ($\Delta P \propto \Delta\sigma_{2D}E_1^2$). To go from a $\sqrt{P}$ to a linear dependence then implies that $\Delta\sigma_{2D}$ is proportional to E_1^2. Such behavior is indeed observed in conductivity measurements on Si/SiGe 2DEGs under microwave radiation [18].

In conclusion, we have presented direct ESR on a single 2DEG in the III-V semiconductor AlAs. At 9.35 and 34 GHz g factors of 1.991 and 1.989 were determined. We demonstrated that the ESR originates from the microwave E_1 field as opposed to conventional ESR that relies on the B_1 field. The ESR is attributed to a periodic modulation of the electron wave vector around k_F due to the E_1 field and the high mobility of the 2DEG. Through spin-orbit interaction, this produces an effective magnetic field that induces the observed spin transitions. Consequently, the temperature dependence of the ESR is much stronger than the 2D magnetization, as it additionally incorporates the temperature dependence of the scattering time of the 2D electrons.

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