Temperature dependence and mechanism of electrically detected ESR at the $\nu=1$ filling factor of a two-dimensional electron system

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(Received 2 July 2002; published 29 April 2003)

Electrically detected electron spin resonance (EDESR) signals were acquired as a function of temperature in the 0.3–4.2 K temperature range in an AlGaAs/GaAs multiple-quantum-well sample at the $\nu=1$ filling factor at 5.7 T. In the particular sample studied, the linewidth is approximately temperature independent, while the amplitude exhibits a maximum at about 2 K and vanishes with increased or decreased temperature. The observed temperature dependence of the EDESR signal amplitude is compared to the theoretical temperature dependence calculated assuming a heating model. The model ascribes the resonant absorption of microwave power of the two-dimensional electron system (2DES) to the uniform mode of the electron spin magnetization where the elementary spin excitations at filling factor $\nu=1$ are taken to be spin waves, while the short-wavelength spin-wave modes serve as a heat sink for the absorbed energy. Due to the finite thermal conductance to the surroundings, the temperature of the 2DES spin-wave system is increased, resulting in a thermal activation of the longitudinal magnetoconductance. The proposed heating model correctly predicts the location of the maximum in the experimentally observed temperature dependence of the EDESR amplitude. These results suggest that EDESR data can be used to discriminate between competing theories for the magnetic ordering and magnetic excitations of a 2DES in the regime of the quantum Hall effect.

DOI: 10.1103/PhysRevB.67.165325 PACS number(s): 73.43.Lp

INTRODUCTION

The interplay between the electron-electron and electron Zeeman interactions in a two-dimensional electron system (2DES) subjected to high perpendicular magnetic field and low temperature leads to a rich variety of phenomena pertaining to the spin excitations and magnetic ordering of the system. Electron spin resonance (ESR) has the potential to serve as a tool for directly probing the electron spin order and dynamics that cannot be obtained by standard transport measurements that probe only the $kl_0 \gg 1$ excitations (where l_0 is the magnetic length) of the system. In principle, the electron dynamics can be probed via extraction of the T_1 or T_2 spin relaxation times from ESR line shape analysis, microwave power dependence, or pulsed (time-domain) methods. However, there are serious technical difficulties that make direct microwave absorption detection of ESR quite problematic in the case of a 2DES due to the low electron densities in single or even multiple GaAs/$Al_{1-x}Ga_xAs$ quantum wells.[1] It has been previously demonstrated that high sensitivity can be obtained if the ESR absorption is detected electrically via a change induced in the magnetoresistance that can be observed under certain conditions in the regime of the quantum Hall effect.[2] This electrically detected ESR (EDESR) method has been successfully used in the analysis of the magnetic field dependence of the bare electron g factor,[3–5] the electron-nuclear interaction and nuclear-spin relaxation rates as a function of filling factor,[6] and the g-factor dependence on the top-gate voltage.[7] Although a variety of phenomena associated with EDESR in quantum Hall systems have been demonstrated previously, there have been no reports describing the underlying physics and a mechanism of the electrical response to ESR transitions. In particular, the temperature dependence of the EDESR amplitude remains to be described theoretically, although there is at least one previous discussion in the literature.[5]

This paper presents an experimental study of EDESR at filling factor $\nu=1$, where the electron-electron and electron spin Zeeman interactions produce an energy splitting in the density of states of the lowest Landau level. In the simplest qualitative description of the electronic transport at $\nu=1$, the Fermi energy is located in the middle of the energy gap due to the spin splitting, and the longitudinal conductivity σ_{xx} vanishes as $T\to 0$. In EDESR, a perturbation of the equilibrium electron spin polarization due to magnetic dipole driven spin-flip transitions produces a photoconductive response. The 0.3–4.2 K temperature dependence of the signal amplitude and resonance linewidth of EDESR has been measured in a 2DES in AlGaAs/GaAs quantum wells for $\nu=1$ at 5.4–5.7 T. The temperature dependence of the signal amplitude is analyzed in detail using the concept of spin waves at filling factor $\nu=1$. For comparison purposes, we also analyze the temperature dependence of the response on the basis of a noninteracting electron spin polarization model. It was determined in a previous study of the nuclear spin-orientation dependence of magnetoconductance that the elementary spin excitations in this sample involve single spin flips rather than multiple spin flips as would be the case for Skyrmion–anti-Skyrmion excitations (sample EA-124).[8] The goal of the present work is to determine if EDESR data can be used to discriminate between competing theories for the magnetic ordering and magnetic excitations of a 2DES in the regime of the quantum Hall effect.

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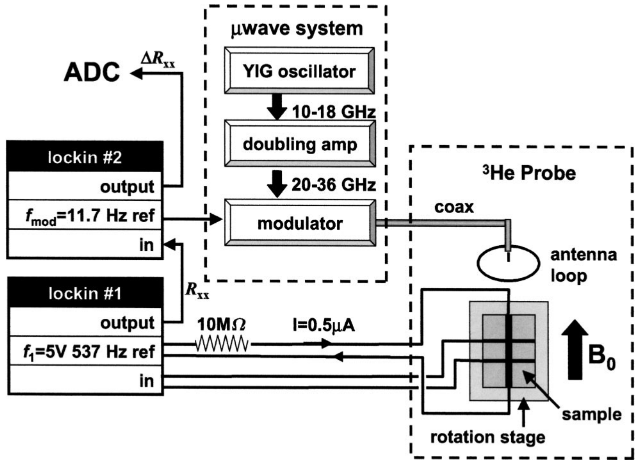

FIG. 1. Block diagram of the experimental setup for EDESR measurements using the double-lock-in technique described in the text.

SAMPLES AND EXPERIMENT

EDESR signals were detected from both multiple and single $Al_{1-x}Ga_xAs/GaAs$ quantum well samples grown by molecular beam epitaxy. These samples have mobilities between $\mu = 4.4\times10^5$ and 1.2×10^6 cm^2/V s and electron densities per layer of $N_s = (7-25)\times10^{10}$ cm^{-2}. Samples were patterned with a conventional Hall bar with a 0.2-mm channel width and a typical voltage probe separation of 1.5 mm. The behavior of the EDESR in all of these samples was found to be qualitatively the same. The experimental data presented below were measured on sample EA-124 (21×300 A wide GaAs wells, $Al_{0.1}Ga_{0.9}As$ barriers). This particular sample has a 2D electron density per layer of $N_s = 6.9\times10^{10}$ cm^{-2} and a mobility of $\mu = 4.4\times10^5$ cm^2/V s. The sample was mounted on a rotation stage, allowing the ESR condition to be obtained at a desired filling factor and magnetic field. The EDESR signals were detected via a change in the longitudinal resistance ΔR_{xx} due to the spin resonance absorption of the microwaves by the 2DES.[2–10] As described previously,[8,9] a double lock-in technique was used to measure ΔR_{xx}. The schematic of the experimental setup is shown in Fig. 1. Lockin #1 is used to apply an AC current [$f_1 = 537$ Hz, 5×10^{-7} A (RMS)] to the sample in series with a 10 MΩ resistor. The microwave system consists of a YIG oscillator (Micro Lambda model MLOS 1392PA) with a tunable output of 10–18 GHz connected to a doubling amplifier (DBS model DB97-0426) which produces a 15 dBm level (into 50 Ω) at the output. The microwave components were connected together using 3.5-mm coaxial connectors and adapters (Anritsu K-connectors). Lockin #2 is used to control an absorptive *p-i-n* diode modulator (General Microwave model D1959) for square-wave modulation of the microwave field at a frequency of $f_{mod} = 11.7$ Hz. The microwaves are applied to the sample via a 50-Ω, 3-mm-o.d. semirigid coax terminated 5 mm above the sample with a wire loop. The output of lockin #1 is a signal proportional to R_{xx}. The R_{xx} signal contains an oscillatory component at f_{mod} proportional to ΔR_{xx}. The time constant of lockin #1 is set to 100 μs while the time constant of lockin #2 is set to 300 ms.

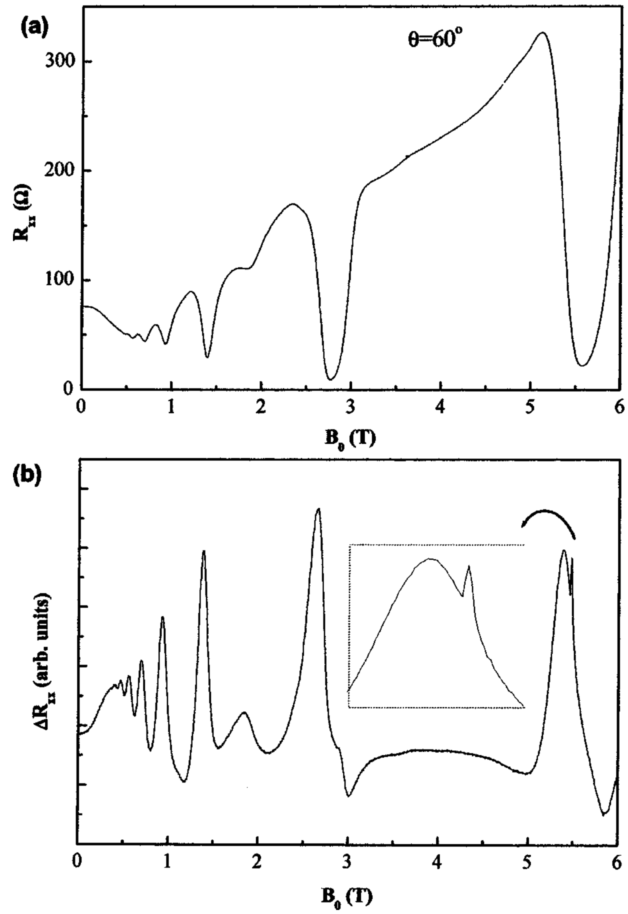

FIG. 2. (a) Typical R_{xx} vs B_0 trace for sample EA-124 at $T = 1.5$ K. The $\nu = 1$ minimum occurs at about 5.7 T. (b) Typical ΔR_{xx} vs B_0 response at $T = 1.5$ K. The sample is tilted at 60° with respect to the external magnetic field. The EDESR signal appears as a sharp peak at $B_0 = 5.47$ T. The inset shows the ESR feature on an expanded scale. The microwave frequency is 32 GHz, which at this magnetic field corresponds to $|g| = 0.418$.

EXPERIMENTAL RESULTS

Figure 2 presents a typical ΔR_{xx} vs B_0 curve together with the corresponding R_{xx} vs B_0 trace, both of which were acquired at 1.5 K. For this experiment the sample was tilted at 60° with respect to the B_0 field in order to bring the $\nu = 1$ magnetoresistance minimum to a field of $B_0 = 5.5-5.8$ T. This field range corresponds to an electron spin Larmor frequency of approximately 30 GHz, a frequency that is within the range of our microwave system. A peak in ΔR_{xx} (B_0) is clearly apparent due to ESR transitions at a field of 5.47 T. The EDESR signal is superimposed onto a nonresonant background contribution to ΔR_{xx}. For magnetic field sweep rates of 0.448 T/min (the highest sweep rate attainable with our magnet), the EDESR signal is the same for both the up- and down-sweep dependences in EA-124. For slower sweep rates, however, effects due to dynamic nuclear polarization (DNP) and the Overhauser shift become

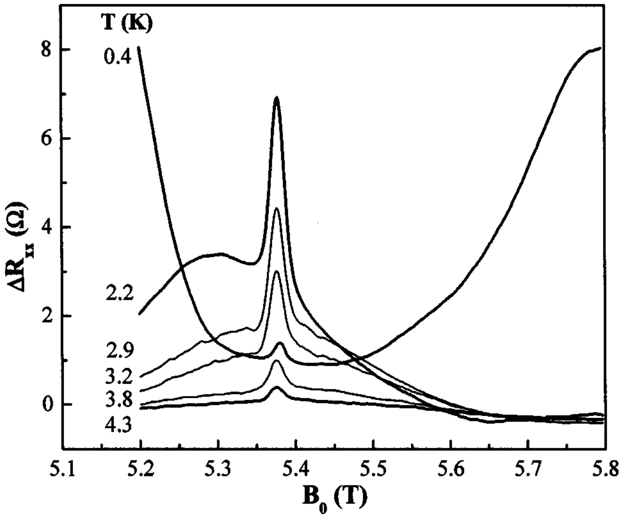

FIG. 3. Experimental ΔR_{xx} vs B_0 curves shown at several selected temperatures, as indicated. The nonresonant background contribution to ΔR_{xx} has not been removed from this raw data. Both the ESR and the nonresonant background contributions to the signal exhibit maximum amplitudes at about 2.2 K.

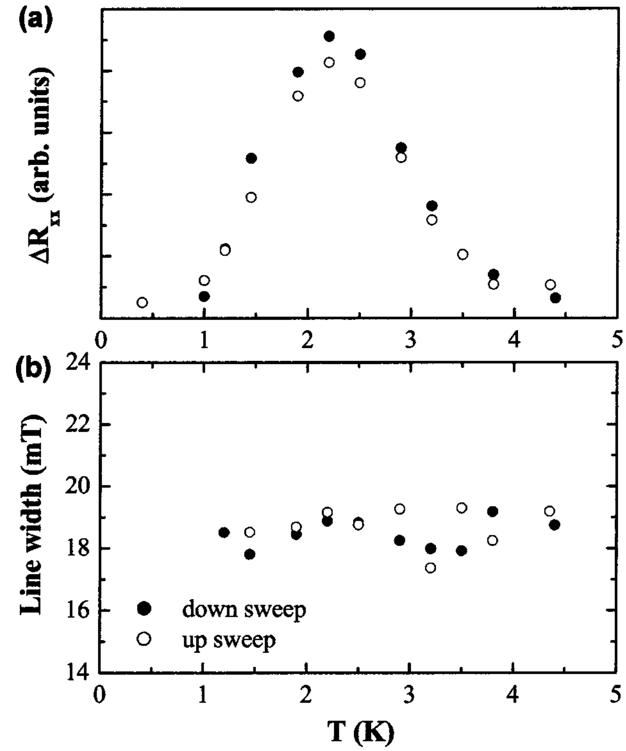

FIG. 4. Temperature dependence of (a) the ESR peak amplitude and (b) the ESR linewidth. The amplitude and linewidths were extracted from the data shown in Fig. 3 after removal of the nonresonant contribution to the ΔR_{xx} vs B_0 signal according to the procedure described in the text.

noticeable. In the down sweep, the EDESR peak broadens and exhibits diminished amplitude, while the signal acquired on the up sweep is narrowed. These observations are consistent with previously reported EDESR experiments involving Overhauser shifts in GaAs/AlGaAs heterostructures.[6,10] All of the spectra presented in this paper have been recorded at the maximum sweep rate of 0.448 T/min. At this sweep rate, the EDESR peak did not exhibit any effect due to DNP. The ESR line position is given by $h\nu_0 = g\mu_B B_{0,\mathrm{esr}}$, where ν_0 is the microwave resonance frequency, $B_{0,\mathrm{esr}}$ is the magnetic field at which the resonance is observed, and g is the bare g factor for single spin flips, which in EA-124 is $g = -0.418$ at the magnetic field of interest. The nonresonant component of ΔR_{xx} is an oscillating function of magnetic field whose main features correlate with R_{xx}. Figure 3 shows the typical EDESR traces measured at different temperatures. These data represent the raw ΔR_{xx} signals that include a nonresonant background contribution. In order to quantitatively analyze the temperature dependence of the signal contribution due to ESR, the nonresonant background component was removed using the following procedure. First, the portion of the raw ΔR_{xx} trace in the region of the EDESR peak was deleted. Using the eye as a guide, several sample points were inserted into the missing region to facilitate interpolation of the background signal. A standard sixth-degree polynomial fit to the background signal was obtained and then subtracted from the original raw data to obtain the component due to ESR absorption. The pure EDESR trace was found to be reasonably insensitive to the particular positioning of the manually inserted sample points and is well described as a Gaussian line shape function. A standard Gaussian fit was then performed on the EDESR trace to obtain the line width and signal integral of the resonance peak. The signal integral will be referred to as the EDESR amplitude for the remainder of this paper. Figure 4 presents the temperature dependence of the EDESR amplitude and linewidth obtained from the raw data of Fig. 3 after removal of the nonresonant background as described above. It is apparent that the EDESR amplitude measured in the vicinity of $\nu = 1$ has a pronounced maximum at about 2 K, decreasing sharply at higher or lower temperatures. As seen in Fig. 3, the ΔR_{xx} nonresonant background component behaves in a similar way, reaching a maximum at the same temperature as the ESR. This behavior is in contrast with that reported in Ref. 5 where the disappearance of the EDESR upon lowering the temperature was accompanied by a growth of the nonresonant background. The linewidth in Fig. 4 appears to be nearly independent of temperature. Assuming that the linewidth is inversely proportional to the spin-spin relaxation time T_2, as in conventional ESR detection by direct microwave absorption, then it may be concluded that T_2 is independent of temperature over the temperature range of interest. We have also measured the filling factor dependence of the ESR amplitude (at constant temperature) in the vicinity of $\nu = 1$, as shown in Fig. 5. The filling factor was varied by incrementally rotating the sample at a fixed microwave power and frequency. Despite the appreciable scatter in the data points, it is apparent that the EDESR signal maximum occurs close to $\nu = 1$. Furthermore, a change in sign of the EDESR is observed for filling factors below 0.94 and above 1.08. In general, the EDESR has been found to have the same sign as the slope of R_{xx} (T) at the same filling factor. The EDESR amplitude decreases upon moving away from $\nu = 1$ where it is positive and exhibits its maximum value, passes through zero at the critical points on

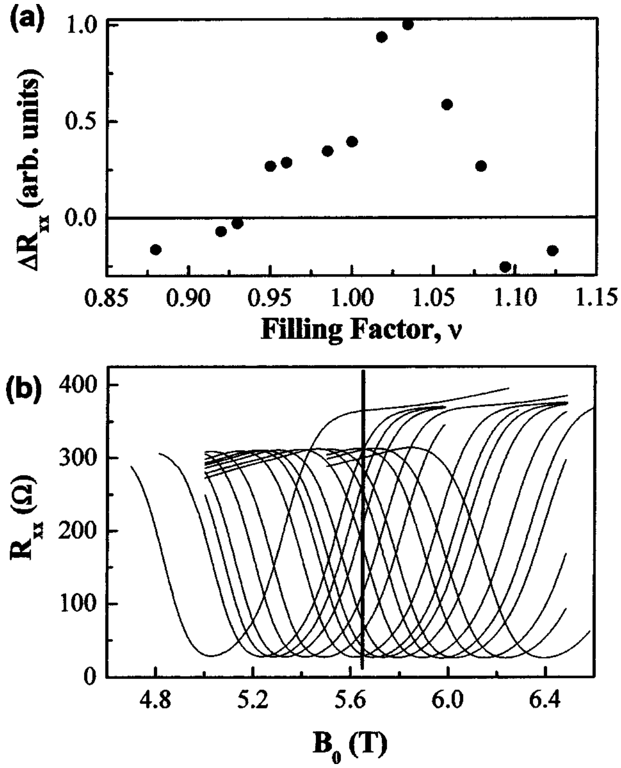

FIG. 5. (a) The EDESR amplitude, ΔR_{xx}, is plotted as a function of filling factor, ν, in the vicinity of $\nu=1$ at $T=1.5$ K. The EDESR exhibits a maximum at roughly $\nu=1$ and changes sign for $\nu<0.94$ and $\nu>1.08$. The sign of the EDESR is correlated with the sign of the temperature dependence of R_{xx}, supporting the proposal that the EDESR mechanism involves a heating effect. (b) Calibration of the filling factor for part (a). The curves represent segments of $R_{xx}(B_0)$ in the vicinity of $\nu=1$ for each tilt angle. To obtain the ESR signal as a function of filling factor the sample was incrementally rotated for each ESR measurement. The microwave frequency was chosen to produce an ESR peak at 5.65 T, as indicated by the vertical line.

both sides of the $\nu=1$ minimum where R_{xx} is temperature independent, and then changes sign at both higher and lower filling factors. Finally, Fig. 6(a) presents a typical activated temperature dependence of R_{xx} at $\nu=1$ in sample EA-124. The activation energy gap determined from this data [see Fig. 6(b)] is 7.0 K, while the single-electron spin Zeeman interaction at 5.7 T is equivalent to a 1.6-K gap. The temperature dependence of the EDESR amplitude, which will be presented in Fig. 9, exhibits a maximum near 1.7 K.

DISCUSSION

We now propose a mechanism for EDESR whereby excitation of ESR produces a change in the longitudinal magnetoresistance, ΔR_{xx}. In the simple density of states model for a 2DES at $\nu=1$ the longitudinal magnetoresistance, R_{xx}, passes through a minimum when the chemical potential is located midway between the maxima in the density of states corresponding to the spin-up and spin-down configurations of the lowest Landau level ($N=0$). The standard method for measuring the spin gap, ΔE, is by an activated transport

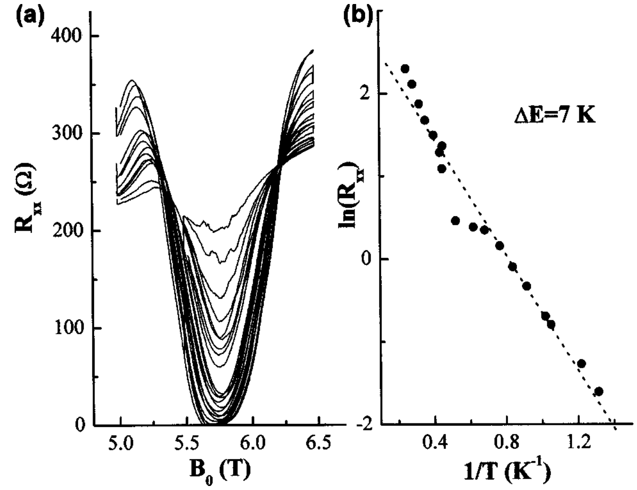

FIG. 6. (a) Temperature dependence of $R_{xx}(B_0)$ in the vicinity of $\nu=1$ at $B_0=5.7$ T. (b) Arrhenius plot of $\ln(R_{xx})$ vs $1/T$ at the $\nu=1$ minimum, which yields a spin splitting of $\Delta E/k_B=7$ K.

experiment wherein the temperature dependence of R_{xx} is fit to the Arrhenius law:

$$R_{xx}=R_0 \exp\left(-\frac{\Delta E}{2k_BT}\right). \tag{1}$$

The prefactor R_0 is related to the sample resistance in the limit $\Delta E \ll k_BT$. The gap ΔE is usually determined from the slope of a plot of $\ln(R_{xx})$ vs $1/T$.

To begin, it should be recognized that the ΔE obtained by fitting Eq. (1) to the temperature dependence of the longitudinal resistance is not the same energy gap associated with EDESR transitions. According to Larmor's theorem, the electron spin Larmor frequency (and the frequency of optical transitions in general) does not depend on Coulomb interactions. In a spin-wave system, the microwave field couples only to the $k=0$ magnetic exciton, where, according to Kohn's theorem,[11] the center-of-mass motion (with $k=0$) is unaffected by electron-electron interactions, so that $\Delta E(k=0)=g\mu_BB_0$. The activated transport experiment, on the other hand, deals with excitations that produce charge carriers via ionization processes. Hence, magnetoresistance measurements probe the large-k limit of the excitation dispersion relation corresponding to a well-separated electron-hole pair. The energy level splittings of the 2DES subjected to a perpendicular magnetic field are usually expressed as a sum of the electron spin Zeeman and the electron-electron Coulomb terms:

$$\Delta E=m\hbar\omega_c+\Delta m_s g\mu_BB_0+\Delta E_c(k,B_0). \tag{2}$$

In Eq. (2), $m=1$ for magnetoplasmons and $m=0$, $\Delta m_s=1$ for spin waves, where ω_c is the cyclotron frequency and $\Delta E_c(k,B_0)$ is the energy contribution due to the electron-electron interaction.[12] Accordingly, the energy gap probed by thermal activation of transport at $\nu=1$ is $\Delta E=g\mu_BB_0+\Delta E_c(k\to\infty,B_0)$. For the magnetic fields pertaining to $\nu=1$ in our GaAs/AlGaAs quantum well samples, the Coulomb term in the $k\to\infty$ limit is much greater than the Zeeman term. For example, $|g|\mu_B B_0/k_B = 1.57$ K at 5.7 T, ΔE_c ($k\rightarrow\infty, B_0 = 5.7T)/k_B = 162$ K. The experimentally measured gap of $\Delta E/k_B = 7$ K in sample EA-124 is substantially smaller than the theoretical gap of an ideal 2DES, presumably due to the inclusion of finite z extent, the influence of disorder, and well-to-well variation in electron density in multiple quantum well samples such as EA-124.[12] Under our experimental conditions, the spin gap measured by thermal activation of R_{xx} is much greater than the Zeeman gap corresponding to ESR transitions induced by a spatially uniform microwave field (relative to the magnetic length). Therefore, a proper description of EDESR at $\nu=1$ in the quantum Hall state must incorporate electron correlation effects. The elementary neutral excitations have been analyzed in the literature as quantized *spin waves* (i.e., magnons) or equivalently as *spin excitons*.[13,14] An important feature of these charge-neutral excitations is that they occur with a conserved wave vector $\vec{k}$, and the excitation of a spin-wave mode corresponds to exactly one electron spin flip which is distributed over many spins.

Our proposal is that EDESR can be conceptualized as a two-step process: (1) the resonant absorption of microwave photons with energy $g\mu_B B_0$ and (2) a resultant increase in the internal energy (i.e., heating) of the 2DES which produces $k\rightarrow\infty$ excitations that are detected via a change in R_{xx} according to Eq. (1). Our model incorporates the dispersion relation for a 2D spin-wave system at $\nu=1$ which has been derived independently by Bychkov *et al.*[14] and Kallin and Halperin:[15]

$$\Delta E(k) = g\mu_B B_0 + \frac{e^2}{4\pi\varepsilon_0\varepsilon l_0}\left(\frac{\pi}{2}\right)^{1/2}\left[1 - e^{-k^2 l_0^2/4} I_0\left(\frac{k^2 l_0^2}{4}\right)\right]. \tag{3}$$

Here, k is the magnitude of the wave vector and I_0 is the modified Bessel function of the first kind. For computational purposes Eq. (3) can be simplified to

$$\Delta E(x)/k_B = 0.27B_0 + 68B_\perp^{1/2}[1 - e^{-x} I_0(x)], \tag{4}$$

where $x = k^2 l_0^2/4$, $l_0 = \sqrt{\hbar/eB_\perp}$, and $B_\perp$ is the component of the applied field perpendicular to the plane of the 2DES. At thermal equilibrium the average number of magnons excited in the mode k is given by the Planck distribution:

$$N_k = \frac{1}{e^{\Delta E(k)/k_B T} - 1}. \tag{5}$$

The total number of modes per unit area is equal to the total number of spins (per unit area) contributing to the magnetization in a 2D layer:

$$\sum_k N_k = \frac{1}{(2\pi)^2}\int_0^\infty \frac{1}{(e^{\Delta E(k)/k_B T} - 1)} d^2k$$
$$= \frac{1}{\pi l_0^2}\int_0^\infty \frac{1}{(e^{\Delta E(x)/k_B T} - 1)} dx. \tag{6}$$

In accordance with Kohn's theorem, only $k=0$ spin-wave modes couple to the microwave field, and the spin resonance energy will occur only when the photon energy of the microwave field equals the single-electron Zeeman energy $g\mu_B B_0$. In our model, the temperature change of the 2DES is due to the deposition of the resonant microwave energy into the $k=0$ excitation. Thus, we need to find a relationship between the power absorbed by excitation of the uniform mode and the observed change in R_{xx} at $\nu=1$.

At low microwave field, the dynamics of the magnetization of a ferromagnetic system can be approximately described by the classical torque due to an effective magnetic field $\vec{B}_{\text{eff}}$ (Ref. 16):

$$\frac{d\vec{M}}{dt} = -\gamma(\vec{M}\times\vec{B}_{\text{eff}}) + \text{dissipative term}, \tag{7}$$

where $\gamma = g\mu_B/\hbar$ is the electron gyromagnetic ratio. According to Bloembergen and Wang,[17] T_1 in ferromagnetic resonance is interpreted as the rate of energy transfer from the uniform mode to the spin-wave modes. Thus energy dissipation can occur either by direct spin relaxation to the lattice or by transfer to the short-wavelength modes followed by relaxation to the lattice. This point will be discussed in more detail below. In the continuous wave EDESR experiment, a linearly polarized, fixed-frequency microwave field with amplitude b_1 is applied to the sample. This field can be decomposed into a left and right circularly polarized component, where the component resonant with the precessing magnetization has the form $\vec{B}_1 = (\frac{1}{2}b_1\cos\omega t, \frac{1}{2}b_1\sin\omega t, 0)$. Additionally, the microwave field is square-wave modulated at $\nu_{\text{mod}} \approx 12$ Hz. The EDESR spectrum is recorded by sweeping the external magnetic field through the resonance. In order for a demodulation signal to appear at the output of the lockin, the ΔR_{xx} response must follow the square-wave modulation of the microwave excitation. The appearance of a signal therefore indicates that the steady state is obtained on a time scale short compared to $1/\nu_{\text{mod}} \approx 83$ ms. The other relevant time constant is $\tau_{\text{ext}} = C_s/K_{\text{bath}}$, where $1/\tau_{\text{ext}}$ is the rate of energy transfer out of the 2DES to the surroundings. For an order of magnitude estimate of this parameter we refer to the heat capacity measurements of a 2DES in GaAs quantum wells around $\nu=1$,[18] which suggest that $\tau_{\text{ext}} \ll 1/\nu_{\text{mod}}$ under our experimental conditions of field and temperature.

It should be noted that in our search to optimize the signal-to-noise ratio we tried a wide range of microwave radiation modulation frequencies. The lowest modulation frequency tried was 1 Hz: the highest was about 30 Hz. For all frequencies in this range the qualitative behavior of the EDESR and its temperature dependence was found to be absolutely the same, even though the amplitude of the EDESR signal at a given temperature as well as the form of the nonresonant background signal could slightly vary with the modulation frequency. Such effects are attributed to phase shifts due to frequency-dependent capacitance coupling in our experimental setup.

To continue, we must make several assumptions regarding the manner in which the EDESR signal is obtained. First, we assume that the "slow-passage" regime, where $d\vec{M}/dt = 0$, is maintained during the field sweep. While the electron spin relaxation times T_1 and T_2 set the time scale for the steady state to be achieved, these relaxation times have never been measured directly for a 2DES at $\nu \approx 1$. However, two-dimensional electron T_1 values on the order of 10^{-9} s have been measured in GaAs quantum wells at low temperature ($\sim$5 K) in the high-field regime by all-optical based measurements of time-resolved electron spin resonance.[19] These measurements provide some evidence that the spin relaxation times are at least several orders of magnitude shorter than the microwave modulation period, even at the lowest temperatures in our study. Moreover, the slow-passage assumption is supported by the observation that both the line shape and amplitude of the ESR peak are insensitive to slight variations in the magnetic field sweep rate, and in addition, we note that the recorded line shape is symmetric.

The steady-state transverse, complex magnetization, given by

$$M_0^+ = \frac{\gamma M_z b_1/2}{\omega_0 - \omega + i\gamma\Delta B_{1/2}/2}, \tag{8}$$

is related to the susceptibility by $\chi = \chi' - i\chi'' = M_0^+/(b_1/2)$, where χ'' represents the loss by the sample and $\Delta B_{1/2}$ is the full width of the resonance curve at half maximum. Thus,

$$\chi''(\omega) = \frac{\gamma^2 M_z \Delta B_{1/2}/2}{(\omega-\omega_0)^2 + \gamma^2(\Delta B_{1/2}/2)^2}. \tag{9}$$

At sufficiently low microwave power, we may make the approximation $M_z \approx M_z^{\mathrm{eq}}$ [the low-power criterion is $(\gamma b_1)^2 T_1 T_2 \ll 1$ assuming a Bloch-Bloembergen dissipation term in Eq. (7)]. The steady-state microwave power absorbed per unit area of the 2D electron spin system may be calculated from

$$\overline{p} = \frac{dQ}{dt} = \frac{1}{4}\chi''\omega b_1^2. \tag{10}$$

On resonance, this simplifies to $\overline{p} = M_z^{\mathrm{eq}} b_1^2 \omega_0/(2\Delta B_{1/2})$.

The magnetization M_z^{eq} can be expressed in terms of the thermal equilibrium electron spin polarization $P_z(T) = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow)$, where $N_\uparrow$ and $N_\downarrow$ are the numbers of spin-up and spin-down electrons. Hence the total magnetization per unit area is $M_z^{\mathrm{eq}}(T) = \frac{1}{2} g\mu_B N_s P_z(T)$. Two different models for the two-dimensional electron system at $\nu = 1$ will be considered. In the first, the thermal equilibrium spin polarization of the spin-wave system is calculated from[20]

$$P_z(T) = \left[1 - \frac{2}{N_s}\sum_k N_k\right], \tag{11}$$

where N_s is the electron spin density and $\Sigma_k N_k$ is given by Eq. (6). For comparison, the second model to be considered is the spin polarization of a noninteracting (paramagnetic) electron spin system:

$$P_z'(T) = \tanh\left(\frac{g\mu_B B_0}{4k_B T}\right). \tag{12}$$

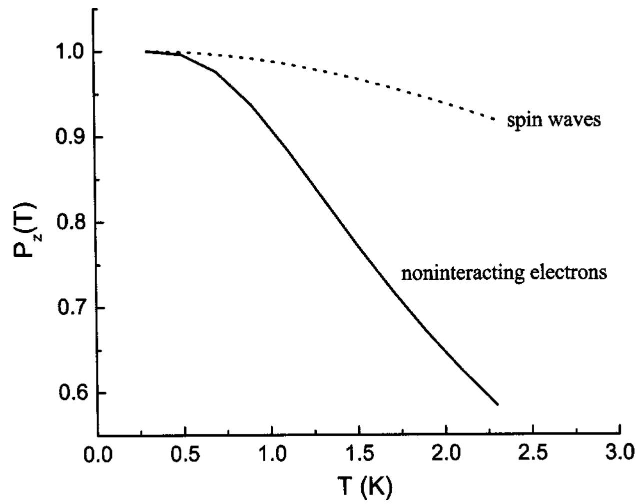

FIG. 7. Theoretical temperature dependence of the spin polarization, $P_z(T)$, at $\nu = 1$ and $B_0 = 5.7$ T for a 2DES in GaAs consisting of either noninteracting electrons [Eq. (12)] or spin waves [Eq. (11)].

Equations (11) and (12) are plotted as a function of temperature in Fig. 7.

The on-resonance microwave power absorbed by the 2DES is $\overline{p} = \hbar B N_s P_z \gamma^2 b_1^2/4\Delta B_{1/2}$, where P_z is responsible for the temperature dependence, can now be calculated. The EDESR line width obtained for EA-124 at 5.7 T and 1.5 K yields $\Delta B_{1/2} = 20 \pm 3$ mT. As is evident from Fig. 4, the resonance linewidth is nearly temperature independent over the temperature range studied. Although in our experimental arrangement there is no way to calibrate the transverse microwave field at the sample, as a rough estimate we take the upper limit to be $b_1 = 1$ mT. The power absorbed from the microwave field by the spin system at spin resonance at 5.7 T and 1.5 K: in the spin-wave model, $\overline{p} = 6.6$ mW/m^2, while in the noninteracting electron model, $\overline{p} = 1.7$ mW/m^2.

Now that we have an expression for the microwave power absorbed, a heat equation can be written:

$$\frac{dU_s}{dt} = C_s \frac{dT_s}{dt} = \overline{p} - K_b(T_s - T_b). \tag{13}$$

As indicated in Fig. 8, T_b is the temperature of the bath, T_s is the temperature of the spin wave system, and K_b is the thermal conductance that determines the rate of heat flow to the surroundings. The steady-state temperature can be obtained by setting $dU_s/dt = 0$, yielding

$$\Delta T = T_s - T_b = \overline{p}/K_b. \tag{14}$$

This establishes the relationship between the change in temperature of the spin-wave system and the microwave power dissipated into the spin system by magnetic resonance absorption.

According to Eq. (1), the variation ΔR_{xx} must be the result of a change in the temperature of the current carriers, which are the magnetic excitations with $k \to \infty$. For an infinitesimal temperature change δT,

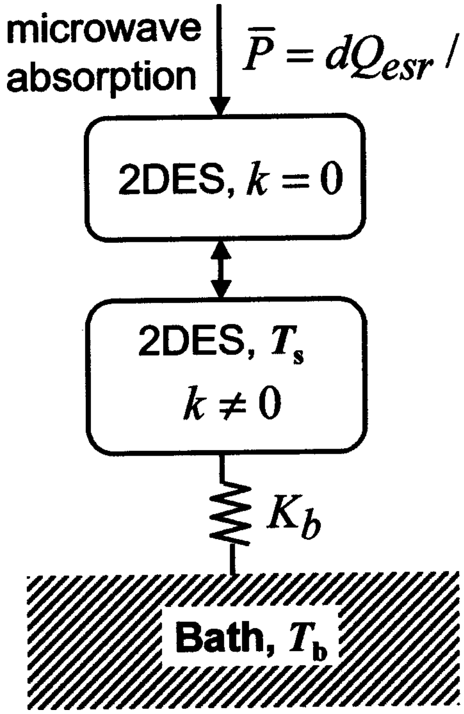

FIG. 8. Electrical circuit diagram equivalent showing energy flow from the microwave field to the spin-wave system and thermal bath. As explained in the text, $\overline{p}$ is the power absorbed by the $k=0$ excitations, while K_b is the thermal conductance from the sample at a steady-state temperature T_s to the thermal bath at temperature T_b.

$$\delta R_{xx} = R_0 \frac{\Delta E}{2kT_b^2} \exp\left(-\frac{\Delta E}{2k_B T_b}\right) \delta T \tag{15}$$

or, more generally,

$$\Delta R_{xx} = R_0[\exp(-\Delta E/2k_B T_s) - \exp(-\Delta E/2k_B T_b)]. \tag{16}$$

A second assumption in our model is that the electron spin system (all spin-wave modes) is describable by a single temperature T_s. This assumption is difficult to verify because even in the steady state it still might not be possible to ascribe a single temperature T_s to all spin-wave excitations. The distribution of energy among the spin-wave modes reached in the steady state will result from a competition between the rate of energy transfer between spin waves and the spin-wave system-to-thermal bath energy transfer rates. To analyze this situation in detail is a difficult theoretical problem that has yet to be addressed for a 2DES at $\nu=1$. Nevertheless, it is possible to proceed if we make the simplifying assumption that a steady state is obtained under ESR excitation that *can* be described by a single temperature T_s.

The idea of heating of the spin-wave system through the resonant microwave absorption and redistribution to the $k \neq 0$ modes by various scattering mechanisms[21] leads naturally to a heating mechanism for the R_{xx} detection of ESR. This model predicts an increase in R_{xx} due to an increase in the spin temperature, in agreement with our experimental data. Furthermore, the model also can be used to calculate

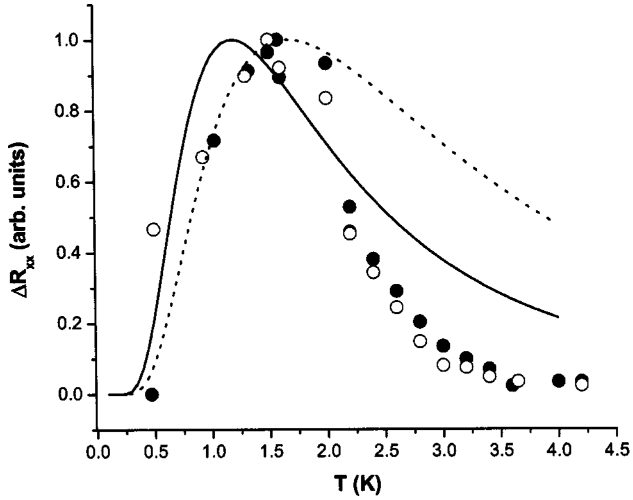

FIG. 9. Experimental data showing the temperature dependence of the EDESR amplitude (after removing the nonresonant contribution to ΔR_{xx}) at 5.7 T. Data points represented by the solid circles correspond to spectra recorded with a magnetic field down sweep, while open circles represent data recorded with magnetic field up sweeps. The $\nu=1$ state is characterized by an activation energy gap of $\Delta E/k_B = 7$ K, as determined from the Arrhenius plot in Fig. 6. The solid curves represent calculations for a 2DES assuming either noninteracting electrons [solid curve: see Eq. (12)] or a spin-wave model [dashed curve: see Eq. (11)].

the temperature dependence of the EDESR response. One can see immediately from Eq. (1) that the slope dR_{xx}/dT is maximized at a bath temperature $k_B T_b = \Delta E/4$ and vanishes as $T_b \rightarrow 0$ or $T_b \rightarrow \infty$. A similar behavior is observed in the temperature dependence of the EDESR response, as shown in Fig. 9. The experimental EDESR amplitude has a maximum at about 1.7 K in a sample state where the $\nu=1$ activation gap is $\Delta E/k_B = 7$ K. Therefore, a heating model is consistent with the experimental data.

Finally, the possibility that saturation of ESR contributes to the decrease in EDESR signal with decreasing temperature needs be considered. The condition for saturation is $(\gamma b_1)^2 T_1 T_2 \gg 1$. Inserting our previous estimates of $b_1 = 1$ mT, $T_1 \geqslant T_2 \approx 3 \times 10^{-9}$ s, we obtain $(\gamma b_1)^2 T_1 T_2 = 2 \times 10^{-4}$. Thus it appears that saturation effects can be ruled out. Future experimental work will entail a complete microwave power dependence study as well as a microwave modulation frequency dependence as a function of temperature.

To calculate the steady-state temperature increase of the 2DES from Eq. (14), a value for the thermal conductance to the surrounding thermal bath is needed. Rather than attempting to calculate K_b, we will use a value that is self-consistent with the experimentally observed increase in the resistance at 1.5 K and 5.7 T according to Eq. (1). The increase in R_{xx} corresponds to a temperature change $\Delta T \approx 10$ mK. This steady-state temperature change, together with the estimate of the power dissipated, allows an estimation of the thermal conductance. For example, $K_{\mathrm{bath}} = \overline{p}/\Delta T_{\mathrm{esr}} \approx 0.66\ \mathrm{W\,K^{-1}\,m^{-2}}$ for the spin-wave model. Assuming that K_b remains roughly constant over the temperature range

0.3–4.2 K and using Eq. (14), the temperature dependence of $\Delta T_{\rm esr}$ can now be calculated. The theoretical temperature dependence of the EDESR amplitude for both the spin-wave and noninteracting models is plotted in Fig. 9. The model based on spin waves assumes the theoretical result[12,15] of Eq. (4) where $\Delta E_c(k\rightarrow\infty)=68B^{1/2}$. The qualitative agreement of either model with the experimental data confirms the validity of the heating mechanism for EDESR. Our theoretical model indicates that the position of the maximum ESR response depends primarily on the activation energy gap ΔE determined from transport, but as is also evident from Fig. 9, electron correlation does affect the position of the maximum and the shape of the temperature dependence.

CONCLUSIONS

The electrically detected electron spin resonance amplitude and linewidth have been measured as a function of both temperature for $T=0.3$–4.2 K and filling factor in the vicinity of $\nu=1$ in a 2D electron system in GaAs quantum wells. The EDESR signal is observed as a sharp peak in ΔR_{xx} when the photon energy of the microwave field is resonant with the Zeeman energy splitting associated with the bare g factor of the electron. The EDESR linewidth is nearly constant in the temperature range studied, while the EDESR amplitude has a maximum at $k_BT\approx\Delta E/4$, where ΔE is the exchange enhanced spin gap determined from thermal activation of transport at $\nu=1$. While the position of the maximum in the EDESR amplitude is sensitive to the nature of the excitations at $\nu=1$, the occurrence of a maximum and the disappearance of the signal as $T\rightarrow 0$ is predicted by a heating mechanism in either the independent electron or spin wave models for the 2DES. This is in contrast to the conclusion reported previously,[5] where data showing the decrease in the EDESR amplitude with decreasing temperature were interpreted as a depolarization of the $\nu=1$ state at low temperatures due to the correlation effects. The proposed heating model correctly predicts the location of the maximum in the experimentally observed temperature dependence of the EDESR amplitude. It also correctly predicts that the signal should vanish as the temperature is increased or decreased. Although microwave saturation effects have been excluded in the signal reduction at the lowest temperatures of the present study, future experimental work will entail a complete microwave power dependence study as well as a microwave modulation frequency dependence. The results of the present study demonstrate how experimental EDESR studies can, under appropriate conditions, provide data that can be used to discriminate between competing theories for the magnetic ordering and magnetic excitations of a 2DES in the regime of the quantum Hall effect.

ACKNOWLEDGMENTS

This work was supported by NSF grant DMR-0106058 and the University of Florida. A portion of this work was conducted at the National High Magnetic Field Laboratory. The NHMFL is supported by NSF Cooperative Agreement No. 0084173 and by the State of Florida.

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