Magnetic Field Pinning of a Dynamic Electron-Spin-Resonance Line in a GaAs/AlGaAs Heterostructure

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(March 22, 2002)

Electrically detected electron spin resonance (ESR) is used to study the hyperfine interaction of the two-dimensional electrons and the nuclei of the host lattice in a GaAs/AlGaAs heterostructure. Under the microwave and radio-frequency double excitations, we have observed that the ESR line can be pinned in a very narrow range of magnetic field - in the vicinity of the nuclear magnetic resonance (NMR) of the nuclei of the GaAs crystal. Our observations suggest that this pinning effect is the result of a competition process between the ESR induced dynamic nuclear polarization and the NMR induced depolarization.

Electrically detected magnetic resonance in variety of GaAs based devices has demonstrated the strong coupling of the two-dimensional electron gas (2DEG) with the nuclear spins of its host crystal. During the electron spin relaxation, the hyperfine interaction triggers a mutual flip of electron and nuclear spins to dynamically polarize the nuclear spins in the vicinity of the 2DEG. As a result of this nuclear polarization and the extremely long nuclear spin relaxation time in the quantum Hall regime, a wealth of dynamic ESR effects, such as Overhauser shift, hysteresis, and instability, are exhibited.

Recently, there are increasing activities using the electron spins in group III-V semiconductors for spin based electronics devices, dubbed as spintronics devices, and for quantum information processing. Although III-V semiconductors are very attractive candidates for these applications due their potential for electron-spin to photon-polarization transfer, all the nuclear isotopes in the crystals have non-zero angular momentum and a strong hyperfine coupling to the electrons. In order to precisely manipulate the electron spins under ESR condition, the aforementioned consequences of the strong hyperfine interaction have to be confronted and better understood.

In an early experiment, Dobers et al. has shown that the nuclear magnetic moment can be altered by applying an radio-frequency (RF) radiation at NMR. Thus, the application of the RF radiation provides control of the local nuclear magnetic moment which in turn has a strong influence on the dynamics of the ESR of the 2DEG. In this paper, we further explore the effect of the RF radiation on the dynamic ESR of a 2DEG in a GaAs/AlGaAs heterostructure by using RF radiation with an extended range of power and field-sweep rate. We report an experimental result that the dynamic ESR signal can be pinned in a narrow range of magnetic field in the presence of RF radiation.

The sample used in this experiment is a GaAs/AlGaAs heterostructure fabricated by molecular beam epitaxy. The details of the sample structure are described elsewhere. The mobility of the sample is 800,000 cm²/V·sec with a density of about 1.6 × 10¹¹ cm⁻², which vary slightly for different cool-downs. Photolithography techniques pattern a 100 µm by 100 µm van der Pauw mesa structure with Ohmic contacts in its four corners. The sample is immersed in the bath of the pumped liquid helium at a temperature of 1.3 K. Applied normal to the plane of a 2DEG is a dc magnetic field produced by a superconducting magnet. Microwave fields transverse to the sample are generated using a short microstrip line that is machined on a commercially available microwave laminate board. Transition from a coaxial cable to the microstrip line is made with an SMA to microstrip board end launch adapter. Opposite the launcher, the microstrip is terminated with a short to ground. The microwave magnetic field circulates about the strip so that when the sample is placed flat on the surface of the microstrip, the ac field is parallel to the 2DEG. Additionally, a single turn coil is placed around the sample, through which an RF field is superimposed onto the microwave field. Use of an RF combiner allows us to supply up to three RF frequencies to the coil and sample simultaneously which enables single magnetic field NMR excitation of the Ga⁷⁹, Ga⁷¹, and As⁷⁵ isotopes.

The experiment is carried out in the quantum Hall effect regime near the Landau level filling factor ν, given by ln(cB), of 3. The odd filling factor regime provides an ideal testing ground to study the magnetic resonance. In this regime, the electrons of the 2DEG at the Fermi level are spin polarized and the resistivity is very sensitive to the spin population and the electronic temperature. Under microwave radiation (> 1 mW at the source) the ESR can be detected directly in Rₓₓ, without microwave modulation, as shown in Figure 1. In literature, it is suggested that the change of the conductivity during ESR is due to absorptive heating of the 2DEG.

Here the linewidth of the observed ESR is not the intrinsic line width, but instead depends primarily on the sweep-rate and sweep direction. Additionally, we find that the ESR peak position depends not only on
FIG. 1. Typical traces of resistively detected ESR spectra for different microwave powers around $\nu=3$. Note the ESR peak shifts to lower B for an increasing power showing strong dynamic polarization and line-broadening. Inset: schematic of the microwave and radio frequency sample coupling structure. The microwave source power was 100 mW.

these sweep parameters but also on the microwave power. Shown in Figure 1 are a set of rather broad ESR lines, about 100 G, which show that as the power of the microwave is increased, the ESR peak shifts towards lower B, further away from its thermal equilibrium position, indicated by the dashed line.

These effects are due to dynamic polarization of nuclei in the vicinity of the 2DEG. As the nuclear spins become polarized, local electrons experience an effective magnetic field in the direction opposite to the applied field. For a fixed excitation frequency, the ESR moves to lower applied magnetic fields for increasing nuclear polarization. This is commonly known as the Overhauser effect. So we believe Figure 1 indicates increasing nuclear polarization for larger microwave power. Between each of these traces the microwave power is turned-off and the sample is irradiated with three RF frequencies corresponding to the NMR of the three nuclear isotopes of the lattice at a single magnetic field. The magnetic field is then slowly swept down through the NMR field. We have found that doing so apparently returns the nuclear polarization to near equilibrium and helps to ensure repeatability between measurements. It is important to mention here that these traces were obtained by rapid increasing-field scans ($> 30$ G/Sec) while irradiating the sample with the same microwave frequency. A fast up-field scan, in which the dB/dt and the rate of change of the resonance position dB$_{res}$/dt are of opposite sign, can always cross to produce an ESR peak. In contrast, with sufficiently strong microwave power, a slow down-field scan can result in a locking of ESR-position to the external applied magnetic field and no ESR peak can be observed. It is apparent from the discussion that the ESR line moves dynamically under strong microwave radiation. Its position is not only power dependent but also can evolve as a function of time.

As indicated in the previous paragraph, the addition RF radiation dramatically changes the behavior of the ESR line. Now we would like to present the main result of the paper: the effect of the RF radiation on the dynamic ESR. Shown in Figure 2, the ESR signal, under additional RF irradiation, is exhibited as a significantly narrower line that is observed in a very narrow range of magnetic field, dependent primarily on the radio frequency. The narrow line can be described as approximately Lorentzian having a half-width at full maximum of less than 10 G and as small as 2 G. The traces shown in Figure 2 are produced by slow decreasing-field scans (dB/dt = -5 G/Sec) while applying a microwave and RF excitation simultaneously. The observed ESR is largely independent of the applied microwave excitation frequency and the lines are effectively pinned to a field determined by the radio frequency. Looking at the figure, varying the microwave frequency from 12.435 GHz to 12.167 GHz, the peak position is almost at the exact same field in each trace. The equilibrium ESR field values for the excitation frequencies used are indicated as the dashed lines in the figure. We found that the narrow line is detectable for fields as far as 4 kG from the equilibrium ESR field.

The narrow peak occurs approximately at the field corresponding to the NMR frequency of $^{75}$As. Figure 3 shows the position of the line as a function of the RF frequency. The plot of frequency versus peak position is displayed on the same figure. The slope of the fitted straight line in the graph, 0.79 MHz/T, confirms the ESR signal is in the vicinity of the NMR of the $^{75}$As nucleus.
Similar experiments, not shown, have been done in the RF frequency range for the Ga\textsuperscript{69} and Ga\textsuperscript{71} nuclei, where the same conclusion can be reached as that for the As\textsuperscript{75} case. This effect can be observed for an RF field as small as \(\sim 10^{-7}\) T (the field is calculated based on input power, cable attenuation and RF coil inductance). We found that the narrow peak is exhibited very weakly or not at all when the equilibrium ESR field is less than NMR magnetic field value. We also found that the field position of the narrow ESR signal depended slightly on the applied power of the microwave radiation. For example, a shift about 10 G is observed when the source microwave power is varied from 1 mW to 32 mW.

The last measurement described here demonstrates the field sweep rate dependence of the observed ESR signal. Figure 4 shows the evolution of the ESR line for sweep rates ranging from - 60 G/s to - 3 G/s (the baseline is subtracted for clarity). For fast scans a broad ESR signal can be seen to rise rapidly from near the equilibrium ESR field of about 22.7 kG. However, as the sweep rate is reduced, the broad signal reduces in intensity leaving the narrow line near the NMR field as the prominent feature, reproducing the signal shown in Figure 2. We would like to note that the observation reported earlier shows close resemblance to our fast sweep rate traces. Also note in the figure that the peak position appears to shift toward higher field for increasing field sweep rates. We believe the scanning rate dependence reveals the competition between the ESR induced dynamic nuclear polarization and the NMR induced nuclear depolarization, as will be discussed later.

Having established the experimental fact that the exhibition of a narrow ESR line can be pinned near the field corresponding to NMR condition, we would now like to discuss the possible origin of this effect.

In magnetic resonance literature, a common case of NMR detected ESR is known to be spectrum hole burning. An inhomogeneously broadened ESR line can be considered as a superposition of independent “spin packets” in different local nuclear environments. Traditionally, a saturated ESR may be de- saturated by applying an NMR excitation at a field within the broadened ESR. The NMR excitation modifies the nuclear field experienced by the electrons changing the ESR condition at that instantaneous magnetic field. First of all, the hole burning picture should only apply to electron spins that are localized (ex. donors in semiconductor) where the statistical variance of the nuclear spin orientation gives rise the inhomogeneous broadening. In our case, the extend of the localized wave function at \(\nu = 3\) is much too large (\(\gg 20\) nm) to consider the 2DEG as localized electrons for the purpose of hole burning, as many wave functions overlap at a given site of nucleus. The inhomogeneous line should thus be averaged out. Furthermore, no saturation is ever observed in our experiment due to the relatively short spin relaxation times of the 2DEG.

One can also imaging that the sweeping of fielded through the NMR would produce an adiabatic fast passage of the nuclear spin. When one sweeps through the NMR fast enough in comparison to the spin relaxation time \(T_{1n}\) of the nuclei, the sign of the magnetization is reversed. Indeed, the \(T_{1n}\) in our experiment is determined to be \(\sim 250\) Sec by the time dependence of the Overhauser shift which is much longer than the field scan passage time. However, we found the ESR position, af-
The effect reported here does not appear to be a common phenomenon 
produced in our numerical simulations. As observed in Figure 4, the onset of the narrow ESR signal occurs because the relaxation rates are not precisely known, we found that the narrow line can be observed for a broad range of parameters. Furthermore, the slow nuclear spin relaxation T_{1n}, due to the absence of the density of states in the quantum Hall regime, makes the dynamic nuclear polarization to be even more prominent. In light of spintronics and quantum information processing applications, we envision that the effect described in this paper can be used potentially for locking a dynamic ESR line to a very narrow range of fields for the spin manipulations. We would like to thank E. Yablonovitch, K. Holczer and S. Brown for stimulating discussions. The work is sponsored by the Defense Advanced Research Project Agency under grant number DAAD19-00-1-0172.

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