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Dynamic nuclear polarization and nuclear magnetic resonance in the vicinity of edge states of a 2DES in GaAs quantum wells

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Abstract

Nuclear magnetic resonance is detected via the in-plane conductivity of a two-dimensional electron system at unity Landau level filling factor in the regime of the quantum Hall effect in narrow and wide quantum wells. The NMR is spatially selective to nuclei with a coupling to electrons in the current carrying edge states at the perimeter of the 2DES. Interpretation of the electron-nuclear double resonance signals is facilitated by numerical simulations. A new RF swept method for conductivity-detected NMR is introduced which offers more efficient signal averaging. The method is applied to the study of electric quadrupole interactions, weakly allowed overtone transitions, and evaluation of the extent of electron wave function delocalization in the wide quantum well.

Keywords: Quantum well; Parabolic Quantum well; ENDOR; Two-dimensional electron system; Quantum Hall effect; GaAs; DNP; Fictitious spin-1/2; Overtone transitions

1. Introduction

Recent interest in spin-based electronics and quantum computing has stimulated numerous experimental and theoretical studies of spin-related phenomena in solid-state semiconductor nanostructures. Magnetic resonance spectroscopy is the ideal tool for evaluating spin interactions, spin-lattice relaxation times and coherence dephasing mechanisms in potential candidate materials for spin-based device applications. Transport detection of magnetic resonance affords several key advantages over conventional resonant cavity or tuned coil methods in quantum confined semiconductors. Most importantly, the limited number of electron or nuclear spins in a nanostructure such as a single quantum dot or quantum well (QW) presents a challenge to the sensitivity of tuned coil or bridge techniques. The inefficiency of detecting MHz or GHz frequency photons is not relevant to optical or charge transport-based detection. Transport detection provides direct access to the spin Hamiltonian and spin relaxation mechanisms relevant to the operation of spin-based devices because the spectroscopy is selective to the conduction channel. Information pertaining to defects [1,2], tunneling [3], and symmetry breaking interactions, which can produce electric quadrupole splittings in NMR [1,4–10] and electron g-factor anisotropy [11–14], can be obtained. Nuclear spin relaxation is found to be extremely sensitive to Landau Level filling [14–16]. The Knight shift [17,18] (i.e. the shift of the nuclear spin Larmor frequency due to coupling to the polarized conduction electron system) can be used to map the electronic wavefunction [19,20] and to

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study spin depolarizing many-body excitations in the quantum Hall effect (QHE) [10,21–25].

Beyond spectroscopic characterization of internal Hamiltonians and relaxation mechanisms, quantum information processing requires (a) preparation of the density operator in a pure state and (b) preparation and detection of entangled quantum states [26,27]. Methods for the manipulation of spin Hamiltonians using RF fields and/or sample rotation, which date back to the spin-echo [28], magic angle spinning [29], and multiple pulse NMR [30], have become increasingly sophisticated over the past 30 years [31,32]. Thus, it is not surprising that some of the first demonstrations of elementary bit operations and entanglement were performed in molecular spin systems [33]. However, molecular systems suffer at least two limitations that are obviated in semiconductor nanostructures: the ability to prepare the system in a pure state and the need for integration with conventional semiconductor electronics. The demonstration of g-factor control in a QW using an external gate [34,35] represents one of the first examples of such integration.

Conductivity-detected magnetic resonance spectroscopy is uniquely suited to studies correlating spin interactions with transport properties of a 2DES [15,25,36]. In magnetoresistivity-detected electron-nuclear double resonance (MDENDOR), NMR spectra are selective to nuclei with an appreciable hyperfine contact interaction to electrons in the path of the source-drain current. At odd-integer filling factors in the regime of the QHE, the MDENDOR spectrum is spatially selective to nuclei with a coupling to electrons in the current carrying edge states which occur within a few magnetic lengths l_0 of the perimeter of the 2DES [37,38].

Here, the in-plane longitudinal magnetoresistance ΔR_{xx} of a 2DES at unity Landau level filling factor in the regime of the QHE is used as the detection channel for ESR and NMR transitions in two different types of remotely n-doped, high electron mobility quantum structures: a superlattice consisting of 21 individual 30-nm-wide square QWs (sample EA124) and a 400-nm-wide GaAs/AlAs digital parabolic QW (sample AG662). It is already well-established that in such structures the nuclear field B_n associated with the electron-nuclear Fermi contact interaction can be enhanced by dynamic nuclear polarization (DNP) [17,18]. The induced nuclear field, in turn, shifts the ESR condition. Consequently, the ESR may become "pinned" to the external field [15,39–41]. NMR is detected via the change in resonant microwave absorption due to perturbation of B_n.

This paper is organized as follows. First, we investigate the effect of increasing B_n on the MDENDOR spectra. The changes are dramatic, but can be interpreted by a simple physical explanation. The hypothesis is confirmed by numerical simulations based on a model for DNP that will be presented. The field swept ^{75}As MDENDOR spectrum acquired at small initial B_n exhibits three resonances. Expression of the spin Hamiltonian and density operators in terms of fictitious spin-1/2 operators permits the change in nuclear field due to selective CW-NMR irradiation of individual satellite and central transitions to be calculated and compared to experiment. These results provide the impetus for the proposal and demonstration of a new RF swept ENDOR technique which facilitates more efficient signal averaging and allows spectra to be acquired at constant applied magnetic field and hence constant Landau level filling factor. The new technique will be demonstrated with (i) a study of electric quadrupole interactions in EA124 and AG662, (ii) observation of weakly allowed overtone transitions of nuclei situated in the conduction channel and (iii) evaluation of the extent of electron wave function delocalization in a wide PQW.

1.1. Quantum wells, energy spectrum of a 2DES, and transport properties

A QW is a conduction band potential energy well formed by sandwiching a relatively low band gap semiconductor between broad barriers of a higher band gap semiconductor. For studies requiring ultra-high electron mobility, the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs/Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ structure (where typically $x = 0.1 \rightarrow 0.4$) has the advantage of nearly perfect lattice matching between the barrier and well layers, yielding interfaces which are nominally unstrained and free of defects. QWs can be grown by various methods, but the highest electron mobilities (c.a. $\approx 30 \times 10^6\,\mathrm{cm}^2/\mathrm{Vs}$) have been achieved by molecular beam epitaxy. To obtain a 2DES in a QW, electrons are introduced by remote silicon δ-doping, where a sub-monolayer of Si is deposited inside the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ barriers. Remote doping eliminates the scattering (and hence increases the mobility) that would result if the Si were deposited directly into the well layer. After cooling to a few degrees Kelvin, a red LED placed near the sample is switched on for a few tens of seconds to ionize the Si donors, resulting in increased 2D density and channel mobility.

At zero field, electrons in a QW move freely in the $x-y$ plane, but their translation along z is quantized into electric subbands. In a square potential well of width W_e, the energy spectrum is given by

$$E_i = \frac{\hbar^2}{2m}(k_x^2 + k_y^2) + \frac{(i\pi\hbar)^2}{2mW_e^2}, \tag{1}$$

where i is the subband quantum number and m is the effective mass. Application of a magnetic field along z confines the motion in the $x-y$ plane to cyclotron orbits, yielding a series of Landau levels for each subband:

$$E_{i,n} = E_i + \hbar\omega_c(n + 1/2), \text{ where } n = 0, 1, 2, \ldots, \tag{2}$$

$\omega_c = eB_\perp/m$ is the cyclotron frequency, $B_\perp = B_0 \cos\theta$ and θ is the angle between z and Z, the direction of the applied magnetic field, B_0. The Landau levels have a degeneracy proportional to $B_\perp$. At high field and low temperature, where $\omega_c\tau \gg 1$ (τ is the scattering time), the energy spectrum