Current-induced nuclear-spin activation in a two-dimensional electron gas

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Electrically detected nuclear magnetic resonance was studied in detail in a two-dimensional electron gas as a function of current bias and temperature. We show that applying a relatively modest dc-current bias $I_{dc} \simeq 0.5$ μA can induce an enhanced nuclear-spin signal compared with the signal obtained under similar thermal equilibrium conditions at zero current bias. Our observations suggest that dynamic nuclear-spin polarization by small current flow is possible in a two-dimensional electron gas, allowing for easy manipulation of the nuclear spin by simple switching of a dc current.

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One of the main problems plaguing the implementation of quantum-information processing schemes in GaAs/AlGaAs quantum dots is the rather short coherence lifetimes of the quantum states, typically lasting only $T^* \sim ns$.[1] An important source of decoherence in these systems is the electron-nuclear-spin interaction resulting from the strong hyperfine coupling between the two-dimensional electron gas (2DEG) and the surrounding nuclei of the GaAs/AlGaAs substrate. While presenting a nuisance for electronic-based quantum information devices, the nuclear spins in semiconductors have themselves been proposed as an alternate candidate for quantum-information carriers[2,3] and their coherent manipulation by pulsed techniques has been demonstrated experimentally.[4] This is particularly appealing due to their high degree of isolation and thus their resilience to decoherence, albeit the polarization of small ensembles of nuclear spins, as well as their addressing and initializing remain formidably challenging experimentally.

It has been well demonstrated that the electron-nuclear hyperfine coupling in GaAs-based systems can be exploited for the electrical detection of nuclear magnetic resonances (NMR) in the quantum-Hall regime.[5–9] For use in quantum information however, the challenge is to both enhance the polarization so as to be detectable and also to have fine control over the full degree of polarization. The nuclear spin in GaAs/AlGaAs can in principle be electrically resolved whenever the average nuclear polarization in a magnetic field is sufficiently large so that electronic transport becomes sensitive to a small change in nuclear-spin orientation through the electronic Zeeman energy. To achieve increased sensitivity, the nuclear polarization can be *dynamically enhanced* through electron-nuclei flip-flopping processes with, for example, electron-spin resonance,[5] edge states in point-contact devices,[10] and recently with single-electron transport in quantum dots.[11,12] Since the nuclear polarization in the presence of a magnetic field follows a Boltzmann temperature distribution, becoming substantial at temperatures below $T \lesssim 100$ mK, the nuclear polarization can instead be enhanced simply by reducing the sample temperature, without recourse to any dynamic polarization schemes.[7–9] While conceptually simple, thermally inducing variations in the nuclear spin lacks the control required to tune the nuclear polarization within time scales on the order of the spin-relaxation time, T_1. In this Brief Report, we perform a two-dimensional frequency-current mapping of the electrically detected NMR signal in the low-temperature regime and find strong evidence that even a modest electrical dc current can polarize the surrounding nuclear spins in a 2DEG. This opens new avenues toward the complete all-electrical control and measurement of the nuclear spins in GaAs/AlGaAs semiconductors.

In the quantum-Hall regime of a 2DEG, the Zeeman energy gap in the noninteracting electron picture is given by $\Delta_Z = g^* \mu_B (B + B_N)$, where g^* is the effective electron g factor, μ_B is the Bohr magneton, B is the applied dc magnetic field, and $B_N = \mathcal{A}\langle I_z \rangle / g^* \mu_B$ is the Overhauser field which depends on the strength of the hyperfine coupling constant $\mathcal{A}$ and the nuclear-spin polarization $\langle I_z \rangle$. Applying transverse RF radiation at the nuclear resonant frequency destroys the nuclear polarization which in turn decreases B_N, thereby altering the electronic Zeeman gap. Due to the negative g factor in GaAs ($g^* = -0.44$), B_N opposes B so that destroying the nuclear polarization increases the overall Zeeman energy. This modification in the Zeeman gap by RF radiation can be electrically detected since, in the thermally activated quantum-Hall regime, the longitudinal resistance is sensitive to the gap energy, $R_{xx} \propto e^{-\Delta/2k_B T}$. This holds true for most filling factors where a minimum in R_{xx} is typically observed at resonance.

This simple picture of electrically detected NMR in the quantum-Hall regime breaks down *de facto* in the first Landau level where in the vicinity of the $\nu = 1$ quantum-Hall state, an "anomalous dispersive" lineshape is observed.[8] At the on-resonance condition $f_{RF} = f_{Larmor}$, the usual resistance minimum is followed by a secondary resistance peak of unknown origin.[8,13–18] Figure 1(a) shows a two-dimensional frequency-current contour plot of the electrically detected NMR signal measured in our sample at $\nu = 0.896$ with some individual spectra shown in Fig. 1(b). At zero dc-current bias we observe the typical dispersive lineshape reported elsewhere.

Our sample is a 40-nm-wide GaAs/AlGaAs quantum well containing a 2DEG with a measured mobility $\mu \sim 16.6 \times 10^6$ cm^2/Vs and electron density $n_e \sim 1.6 \times 10^{11}$ cm^{-2}. NMR measurements were performed at fixed field by continuously shining transverse RF radiation at constant power while sweeping the RF frequency through the Larmor resonance condition. Resonance was observed via electrical-transport measurements using a standard lock-in technique

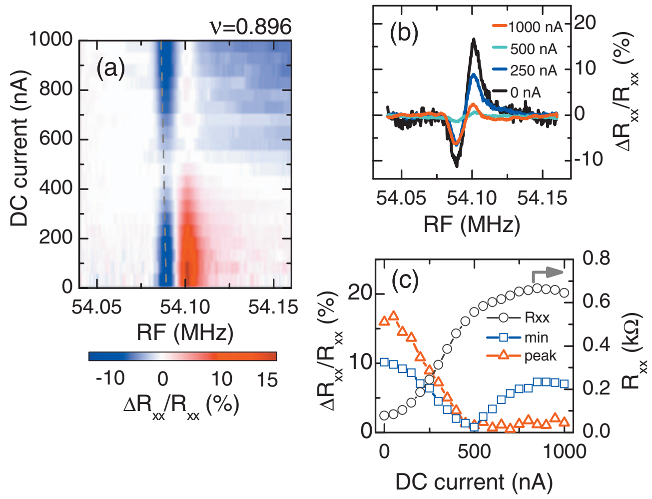

FIG. 1. (Color) (a) 2D contour map of the NMR lineshape versus dc-current bias at ν=0.896 and T_e=34 mK at I_{dc}=0 nA. Dashed line indicates the estimated magnet drift during the scan. (b) Selected traces from the contour plot in (a). (c) Normalized minima (open squares) and peak (open triangles) versus dc-current bias, plotted along with the corresponding off-resonant background resistance (open circles).

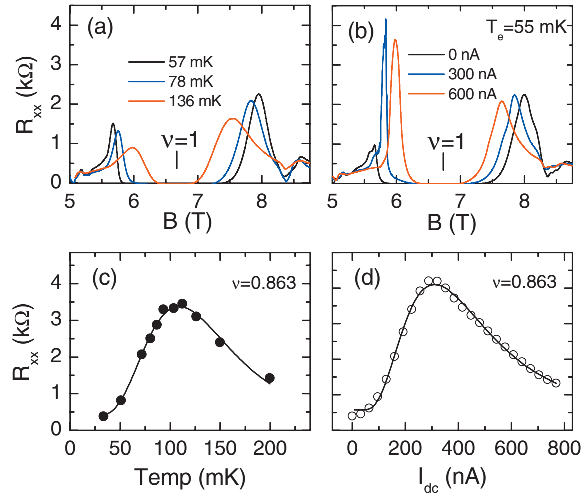

FIG. 2. (Color) [(a) and (b)] Variation in the longitudinal resistance, R_{xx}, around the ν=1 quantum-Hall state due to (a) sample heating by raising the fridge temperature and (b) applying a dc-current bias. [(c) and (d)] R_{xx} versus sample temperature and applied dc current, respectively, at filling ν=0.863 (B=7.800 Tesla). Data in (c) and (d) were acquired at fixed field, on a separate cool down from the data in (a) and (b).

at low frequency (~10 Hz) and small excitation currents (~10 nA). All NMR measurements are reported for the ^{75}As nuclei only; measurements of the Ga isotopes are expected to give the same result.[8,14] The temperatures quoted are the electron temperature, calibrated against a cerium magnesium nitrate thermometer and superconducting fixed points, and corrected for nonresonant RF heating.

The most striking feature of the data shown in Fig. 1(a) is the variation in the NMR signal with increasing dc-current bias. As I_{dc} is increased, electron heating causes a variation in the off-resonant value of R_{xx}. For ease of comparison we therefore plot the variation in R_{xx} observed at resonance, normalized to the corresponding off-resonant value, $\Delta R_{xx}/R_{xx}$. The data was acquired by stepping I_{dc} in regular intervals and sweeping the RF frequency through resonance at each current value. During each scan, the magnet was held persistent. The frequency sweep time at each interval, plus a ~10 min pause between intervals, gave a total scan time of ~10 h for the whole plot. The dashed line indicates the expected magnet drift over this scan time, estimated by repeatedly measuring the NMR signal over a similar time scale. From the contour plot, we observe the following evolution of the NMR signal: (i) both the minimum and peak features initially diminish, nearly vanishing at $I_{dc}\sim 500$ nA; *ii)* as I_{dc} is further increased the minimum reappears and gains in intensity with I_{dc}. Our basic result, i.e., the reentrance and the strengthening of the signal above a critical dc-current value $I_{dc}\gtrsim I_c$ has been reproduced at other filling fractions in the flank of the ν=1 quantum-Hall state.

Application of a dc current causes heating of the electron gas. The initial diminishing of the NMR signal therefore could be understood as a consequence of associated thermal destruction of the nuclear polarization. The thermal distribution of the nuclear-spin magnetization should roughly follow that of a Curie law $\langle I_z\rangle \propto B/T$ when $\mu_N B \ll k_B T$, i.e, in the high-temperature/low-field limit. Increasing the sample temperature should therefore reduce the nuclear-spin polarization and restore the electronic Zeeman gap to its "nuclear-spin-free" value. Consequently, the electrical NMR signal strength $\Delta R_{xx}/R_{xx}$ is expected to vanish monotonically to zero with increasing temperature, consistent with the initial trend in Fig. 1(a). However, in this view, the subsequent reentrance of the NMR signal at higher dc-current values is unexpected. The reemergence of the NMR signal at increased dc-current bias, where thermal effects are expected to further destroy the nuclear polarization, suggests enhancement of the nuclear-spin state by dynamic nuclear polarization (DNP) (Refs. 15, 19, and 20) may be at play.

To deconvolve contributions from the dc current and thermal effects we compare the results of sample heating due to application of a dc current, versus heating the sample directly by raising the fridge temperature. Figure 2(a) shows the effect of increasing the electronic temperature on the ν=1 quantum-Hall state when the refrigerator temperature was increased. This causes a convergence of the resistance peaks on either side of the minimum. As a result, at fixed filling factor [Fig. 2(c)], R_{xx} first increases with temperature ($dR_{xx}/dT>0$), only to decrease with further heating ($dR_{xx}/dT<0$). Applying a dc-current bias I_{dc} through the electrical leads contacted to the 2DEG gives a nearly identical trend, as shown in Figs. 2(b) and 2(d). Using R_{xx} as a thermometer, the electron heating due to I_{dc} was estimated by comparing the variation in R_{xx} under application of the dc current [Fig. 2(d)] with the variation in R_{xx} observed when heating the sample by raising the fridge temperature [Fig. 2(c)].[21,22] The correspondence between $R_{xx}(I_{dc})$ and $R_{xx}(T)$ in the $\nu\sim 0.86$ region in Fig. 2 indicates that likewise $dR_{xx}/dI_{dc}\propto dR_{xx}/dT$. This suggests that the reentrance of the NMR signal we observe in Fig. 1 is not simply due to a crossover in the sign of dR_{xx}/dT (Ref. 13) since the signal is

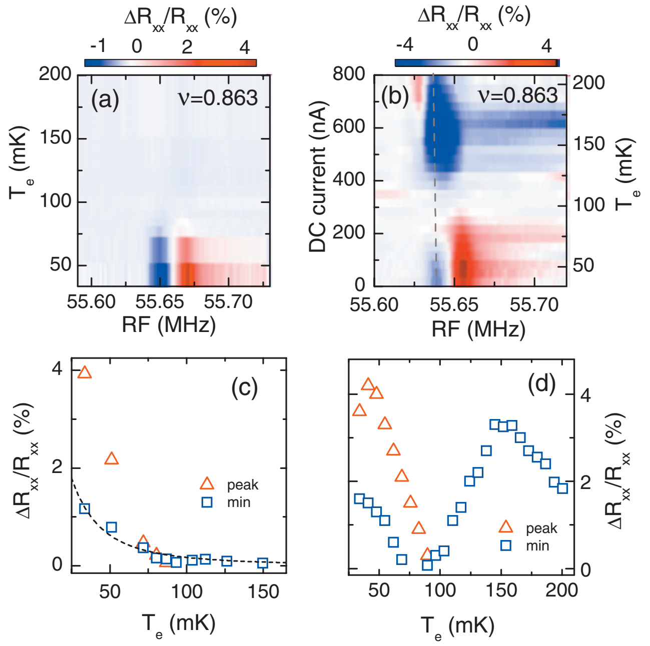

FIG. 3. (Color) Contour plot of the dispersive lineshape at $\nu=0.863$ under (a) varying fridge temperature and (b) applied dc-current bias. The right axis in (b) shows the associated electron temperature, estimated from Fig. 2. In (c) and (d), the magnitude of the normalized signal ($\Delta R_{xx}/R_{xx}$) is shown versus electron temperature for each data set in (a) and (b), respectively. Squares (triangles) label the minimum (peak) response. Dashed curve in (c) is a fit to the hyperfine interaction model to the NMR minimum (see text).

observed to vanish at $I_{\rm dc}\simeq 500$ nA and then reappear where R_{xx} is still increasing with $I_{\rm dc}$, i.e., in a region where $dR_{xx}/dT \propto dR_{xx}/dI_{\rm dc}$ is always positive.

In Fig. 3 we show a direct comparison of the NMR signal evolution obtained by varying the fridge temperature with no dc current applied [Fig. 3(a)] versus applying $I_{\rm dc}$ at base temperature [Fig. 3(b)]. This data was acquired at the same filling factor as the data in Fig. 2 ($\nu=0.863$), allowing us to calibrate and compare the electron heating due to the dc current. When heating the sample by increasing the fridge temperature, the NMR signal initially diminishes with increasing T_e and approaches a vanishingly small signal intensity at electron temperature $T_e \sim 100$ mK. This behavior is similar to that observed at low current bias prior the reentrance of the NMR signal, indicating that in both cases, the weakening of the NMR signal in this regime is likely a purely thermal effect. The NMR minimum, in the thermally activated regime, is believed to result from the hyperfine interaction as described above. According to this model, the normalized variation in magnetoresistance at resonance can be written as $\Delta R_{xx}/R_{xx}=(1-e^{-g^*\mu_B(B_N-B_N')/2k_BT})$, where R_{xx} is the off-resonance magnetoresistance, B_N is the off-resonance Overhauser field, and B_N' is the diminished field on resonance resulting from RF destruction of the nuclear polarization. As a first-order approach, we can write $B_N-B_N'=\alpha B_N$, where α is left as a fitting parameter. From the Curie law $B_N=\mathcal{A}\mu_N(I+1)B/g^*\mu_B 3k_BT$, where I is the nuclear spin, μ_N is the nuclear magneton, and B is the dc polarizing field, which gives $\Delta R_{xx}/R_{xx}=(1-e^{-\alpha\mathcal{A}\mu_N(I+1)B/6k_B^2T^2})$. The dashed line in Fig. 3(c) represents a fit to this equation, showing good agreement with the temperature-dependent behavior of the NMR minimum (open squares). Away from exact filling, the behavior of R_{xx} is quite complicated and is not expected to follow a simple thermal-activation behavior, in general. However, we find that by normalizing out the R_{xx} dependence, the simple hyperfine model can describe our data, which in turn gives further support that the magnitude of the NMR signal is limited by the thermally populated nuclear-spin polarization.

The NMR peak behavior (open triangles in Fig. 3) shows a markedly different trend from the minimum, which we were not able to fit using the same model. This is not surprising since the hyperfine interaction is not able to explain the peak response, whose origin remains unknown and controversial. A full microscopic description of the R_{xx} behavior in this regime would certainly lead to a better understanding of the full nature of the electrically detected NMR signal shape, however this remains a formidable theoretical challenge.

Under application of a dc current, we observe a remarkably strong enhancement in the magnitude of the NMR minimum [Fig. 3(d)]. At $I_{\rm dc}\sim 650$ nA, where we estimate the electron temperature to be ~ 160 mK, the magnitude of the normalized NMR minimum is nearly twice its initial value and exceeds that of the thermally induced signal (at the same electronic temperature) by a factor of ~ 50. A persistence of the signal to large dc-current values could be explained by the current-induced heating predominantly affecting the electron temperature without changing much the nuclear temperature. This might be expected since at very low temperatures, as in our experiment, the electrons may not be that well thermally coupled to the lattice. However, the observed *enhancement* in the NMR minimum, increasing by nearly a factor of 2 for $I>I_c$ is strong evidence that the applied dc current actively *enhances* the nuclear polarization.

We also note in Fig. 3(b) that the peak signal reemerges at high dc-current bias but appears downshifted, occurring at a lower frequency position than the minimum, consistent with the NMR lineshape inversion reported previously.[13,23] Since the origin of the peak in the dispersive lineshape is unknown, it is difficult to understand the mechanism that causes an apparent shift in the peak position. However, this observation rules out the possibility that the enhanced minimum at high $I_{\rm dc}$ is somehow the result of the initial minimum and peak signals collapsing onto a single response and therefore further supports our interpretation that the signal enhancement results from a current-induced DNP process.

The reentrance, persistence, and even the strengthening of the NMR signal with applied dc current constitute a collective set of evidence for DNP induced by the current. This is consistent with previous reports of current-induced DNP.[10,15,19,20] In DNP, nuclear-spin polarization is induced through nonthermal dynamical processes where electron-nucleus flip flop via the hyperfine Hamiltonian $\mathcal{H}=\mathcal{A}\vec{I}\cdot\vec{S}=\frac{\mathcal{A}}{2}[I_+S_-+I_-S_+]+\mathcal{A}I_zS_z$. For this to occur, spin-flip scattering of electrons is necessary, which is known to be occurring between spin-resolved quantum-Hall edge channels, or with domain structure of different spin configurations. Recent work by Kawamura *et al.*[19] suggested that DNP is possible in principle in bulk 2DEG provided the dc current exceeded a threshold value $I_c \gtrsim 0.3-1.0\ \mu A$. Their findings are fully consistent with ours and support the view that DNP can occur with relatively small electrical currents.

In summary, we report on a dc-current-induced reentrance of the anomalous dispersive NMR lineshape observed in the vicinity of $\nu=1$ quantum-Hall state. Comparing the effects of a dc-current bias with those of direct sample heating, we conclude that two distinct mechanisms are at play in the detection of the NMR signal electrically, one that is purely thermally activated and the other due to the current flow intensity. Our observation of an increase in the NMR signal at large dc-current bias is strong evidence for a current-induced nuclear-spin enhancement by means of dynamic nuclear polarization. Our observation that the nuclear-spin signal can both be diminished and enhanced by varying a single parameter, i.e., the applied dc-current amplitude, is of high relevance toward realization of nuclear-spin-based devices.

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