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13. ABSTRACT (Maximum 200 words)

This research explores the possibility of building a semiconductor-based quantum Hall quantum computer. The aim of this study is to develop the technology to initialize, measure, and manipulate the spin polarization of nuclei in semiconductor nanostructures, which could constitute the quantum bits (qubits), and obtain electrically controlled, electron mediated spin interaction between nuclear spin domains. The physical mechanism to be utilized here for the handling of nuclear spins is the hyperfine interaction, which will be used to pump- and detect- nuclear polarization via Electrically Detected Electron Spin Resonance (EDESR) under microwave excitation. A hyperfine interaction / EDESR based scheme has the advantage that only nuclei in the immediate vicinity of the relevant confined electrons can, via the flip-flop interaction, obtain spin polarization from electrons. Thus, one can obtain spatial selectivity in the polarization and measurement of spin. Indeed, in gated devices where even the presence of electrons can be switched electrically, one can then electrically select the ensemble of nuclei that are to obtain polarization and control their number through the choice of gate size. The study will aim to refine and improve the sensitivity of EDESR and EDNMR (Electrically Detected Nuclear Magnetic Resonance) techniques and apply them to progressively smaller structures. The project will also investigate both experimentally and theoretically, the nature of electron mediated spin transfer between nuclei, and the coherence and relaxation times of spins in nanostructures.

14. SUBJECT TERMS
Quantum Computing, Low Dimensional Electron System, Nuclear Magnetic Resonance, Electron Spin Resonance, Quantum Hall effect

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Final Progress Report: DAAD-19-01-1-0607

Project: Measurement and manipulation of nuclear spins embedded in low dimensional quantum Hall electronic semiconductor systems: A novel experimental approach to quantum computation

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Statement of the problem studied:

The recent emphasis on spintronics and spin-based semiconductor quantum computing has increased the interest in the spin degreee of freedom, and especially semiconductor systems that allow for the control of spin.[1-12] Low Dimensional Electronic Systems[LDES] have consequently drawn attention because, at high magnetic fields and low temperatures, they include special properties, which make possible relatively simple electrical detection- and rf/microwave control- of nuclear- and electronic- spins.[13,14] In particular, microwave induced Electron Spin Resonance (ESR) can be resistively detected in the quantum Hall regime, the ESR can be utilized to build up nuclear polarization via the flip-flop interaction, and the nuclear spin state can be subsequently characterized, through an electrical measurement, by examining the back action of the nuclear magnetic field on the ESR.[14-20] Such electrical characterization techniques are valuable because they provide spatial resolution, and can potentially help to characterize the spin state of the system over microscopic length scales. In our ARO-sponsored experimental research program, we have been applying this approach for the initialization, control, and readout of the nuclear spin polarization in spin domains within the LDES, with a view towards spintronic and quantum computing applications. The goals have been to develop the capability to measure and control a spin domain, scale down its size to reduce the number of spins per domain, and finally realize the capacity to simultaneously handle, i.e., measure and control, a multiplicity of domains on a single chip. Progress thus far indicates that the envisioned measurement and control schemes function as expected in the quantum Hall regime. Indeed, the research has already identified a relatively simple and promising method for setting- and simultaneously measuring- the polarization of a nuclear spin system in the quantum Hall regime.[17-20]

Background: Nuclear Spin Manipulation in the Quantum Hall Regime

A two-dimensional electron system subjected to high magnetic fields exhibits a discrete electronic spectrum due to Landau quantization.[13] In the presence of disorder, there is a broadening of the Landau levels, with a localization of states between the Landau subbands, in the low temperature limit. When the Fermi level in the 2DES is pinned amongst the localized states within the mobility gap, the quantized Hall effect is manifested by zero-resistance states, i.e., R_{xx} -> 0, and Hall plateaus where the Hall resistance, R_{xy}, in quantized units of h/e^2. In this quantum Hall context, zero-resistance is the asymptotic behavior in the zero-temperature limit. In practice, at liquid helium temperatures, a small but finite resistance is observed, the resistance is strongly temperature dependent, and it is described by an activation law, i.e., $R_{xx} \sim \exp(-T_0/T)$, where T_0 is an activation energy. [13]

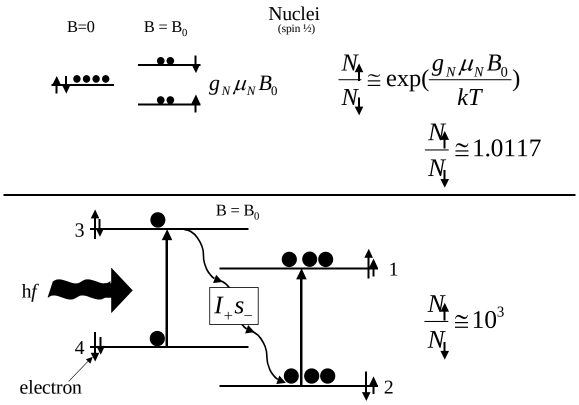

Fig. 1) (Top) A nuclear spin system exhibiting a Nuclear Magnetic Resonance (NMR) frequency of, say, 7.3 MHz/Tesla shows nearly equal occupancy of the up and down spin levels under typical experimental conditions. (Bottom) The nuclear spin polarization can be boosted under the same conditions by saturating the Electron Spin Resonance (ESR) in a coupled electron-nucleus system.

A non-vanishing electronic g-factor helps to remove the spin degeneracy of the Landau bands by giving rise to a spin splitting. When the Fermi level is pinned in the localized states between spin split subbands, the system exhibits once again activated transport that leads into zero-resistance states and quantized Hall effect. Under these conditions, the incompressibility and activated transport conspire to produce conditions that are especially favorable for the manipulation and measurement of nuclear and electronic spins in such systems. In particular, the incompressibility makes the system relatively inert to other low energy perturbations so that Electron Spin Resonance induced, for example, by microwave excitation, becomes

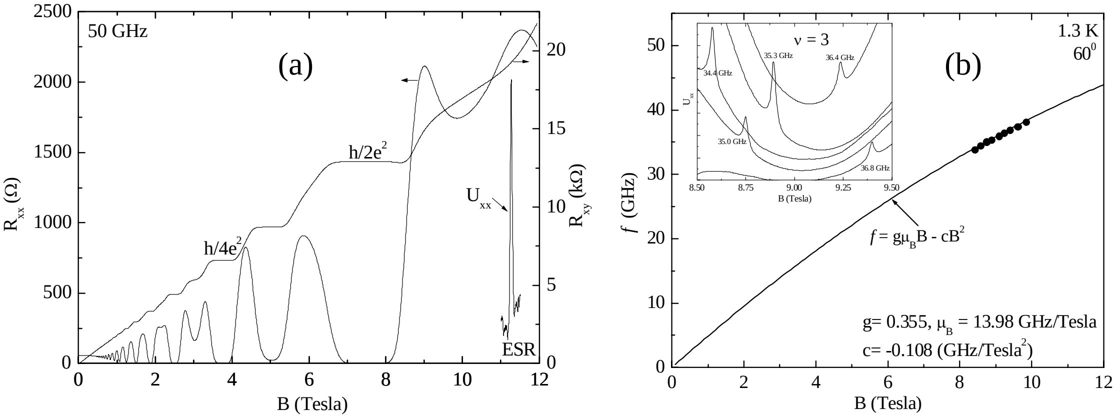

Fig. 2) (a) The magnetoresistance (R_{xx}) and the Hall resistance (R_{xy}) of a GaAs/AlGaAs heterostructure device, which shows quantum Hall characteristics, under microwave excitation at T = 1.3 K. The microwave induced voltage U_{xx} shows Electron Spin Resonance (ESR) at B ≈ 11.3 Tesla for f = 50 GHz. (b) Electron Spin Resonance frequencies as a function of the magnetic field in a GaAs/AlGaAs device at 1.3 K about filling factor ν = 3 at a tilt angle of 60^0. The inset illustrates the ESR line for a number of frequencies.

readily observable in the electrical response, as a consequence of the strong temperature sensitivity, which originates from the activated resistance in this regime.[14,21] Further, under steady state ESR, the decay of spin-excited electrons leads to the spin polarization of nuclei via the flip-flop, electron-nuclear hyperfine interaction. The magnetic field arising from the spin polarized nuclei then provides a back action on the electrons, leading to an Overhauser shift in the electrically detected ESR, which can serve to characterize the nuclear spin system. Thus, the availablity of such electrical detection techniques makes possible spatially resolved characterization and control of both nuclear and electronic spins in quantum Hall systems. Such systems provide additional flexibility to the experimenter because the nuclear spin relaxation times are relatively long (~10^3 sec), and they can be adjusted by setting the diagonal resistance of the specimen.

The spin-spin interaction between an electron, S, and a nucleus, I, is described by the hyperfine interaction hamiltonian, $A\mathbf{I}\bullet\mathbf{S} = A((I_+S_- + I_-S_+)/2 + I_zS_z)$.[22] For spin-1/2 particles, the diagonal component (I_zS_z) indicates a four - level system (see Fig. 1, Bottom), where the eigenvalues are labeled by the z-component of the spin of the constituent particles. The saturation of the electron spin resonance in such a system by the application of intense microwave radiation tends to equalize the electronic population of the levels. Then, the coherent ‘flip-flop’ type exchange of spin between electrons and nuclei through the off-diagonal term provides a mechanism for realizing a steady state (see Fig. 1, Bottom), that includes a large population difference between the nuclear spin states.[21] That is, the off-diagonal term implies that steady state ESR can dynamically polarize the nuclei within the extent of

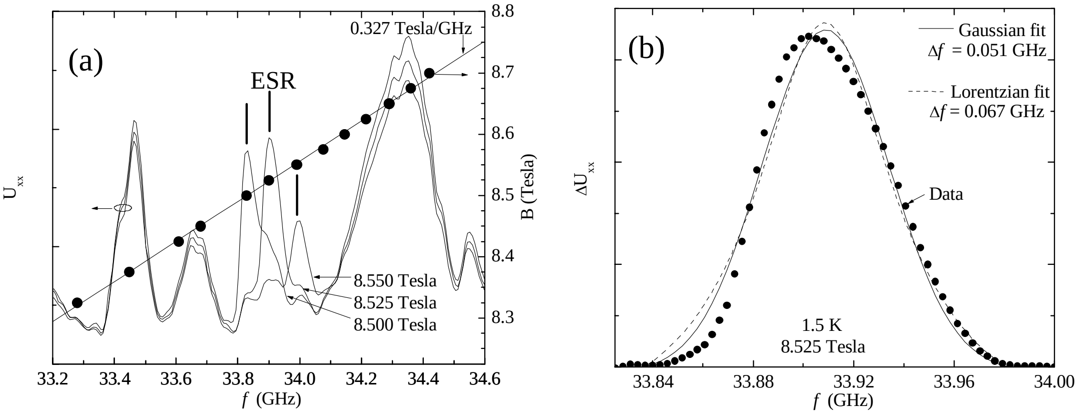

Fig. 3) Electron Spin Resonance observed at fixed magnetic fields in a GaAs/AlGaAs device upon ramping the microwave frequency. (a) The signature of Electron Spin Resonance is the sensitivity of the U_{xx} signal to B over the interval 33.8 GHz < f < 34.1 GHz. (b) U_{xx} vs. f at B = 8.525 Tesla shows the lineshape. Also shown are Lorentzian and Gaussian fits to the data.

the electronic system, as spin-excited electrons swap spin with the nuclei during the relaxation process. Indeed, the Boltzmann factor describing the steady state nuclear spin polarization comes to be determined by the electronic spin-flip energy (Fig. 1, Bottom), instead of the nuclear spin flip energy (Fig. 1, Top). Thus, it is, in principle, possible to realize a large nuclear spin polarization using this technique at a high temperature.[21] Since nuclei possess a magnetic moment that goes together with their spin, a build up of the nuclear spin polarization by ESR also generates a substantial associated nuclear magnetic field, B_N, which modifies the spin resonance condition for electrons. Under dynamic nuclear polarization by ESR, the ESR condition becomes $g\mu_B(B + B_N) = hf$, where hf is the photon energy and $g\mu_B B$ is the electronic spin splitting in the absence of nuclear polarization. Thus, with the build up in the nuclear polarization, there is a characteristic B-field shift of the ESR in proportion to the nuclear magnetic field, B_N.[21] This shift, called the Overhauser shift, makes it possible to characterize the nuclear spin state through a measurement of the displacement of the electrically detected ESR. In addition, dynamic nuclear plarization implies that the electrical resistance becomes sensitive to the nuclear spin state, implying the possibility of nuclear magnetic resonance detection through a resistance measurement.[14-20]

Such physical phenomena can be utilized to realize discrete, independently controlled, and separately measured nuclear spin domains. In particular, nuclear spin initialization can be achieved at a relatively high temperature by applying the dynamic nuclear polarization described above (Fig. 1, Bottom). Thus, the writing, say, of a ‘1’ state on a spin domain is accomplished by harnessing the flip-flop interaction between conduction electrons undergoing spin resonance (due to microwave irradiation) and the nuclear spins. The '0' state then follows from the '1' state through the application of a radio-frequency π-pulse that rotates the spins by 180^0. A local operation on a single domain can be implemented by introducing or removing electrons into the nuclear neighborhood using a voltage controlled ‘gate,’ as the specimen is irradiated with a global microwave field. The nuclear spin remain unaffected by the radiation if free electrons do not occur in the immediate vicinity because the microwave radiation can only operate on the electrons and the electrons are necessary to operate, in turn, on the nuclei. A superposition of ‘1’ and ‘0’ states can be realized by initializing a domain to a ‘1’ state and then subjecting it to resonant radio frequency $\pi/2$ pulse, which rotates the spins by 90° with respect to the quantization axis. Readout of the nuclear spin state is accomplished by detecting the shift in the electrically detected ESR due to the nuclear magnetic field. Here, the '1' and '0' states will exhibit Overhauser shifts in opposite directions, while state superposition would be reflected as Rabi oscillations in the Overhauser shift. According to the theoretical studies of Taylor and co-workers,[23] an ensemble of nuclei, i.e., a nuclear spin domain, can serve as a repository or storage media for the quantum information associated with a mobile electronic qubit, and it is possible, in principle, to transfer quantum information in both directions between the mobile qubit and the nucler spin domain with high fidelity. The operations described above can serve to prepare the spin domains for such a function.

Summary of results:

Spin resonance and dynamic nuclear polarization in quantum Hall systems

We now demonstrate the viability of this approach, and illustrate some of the associated concepts, through experiment. For this purpose, measurements were carried with GaAs/AlGaAs specimens mounted inside a waveguide within a low temperature cryostat, which was fitted with a superconducting magnet for operation over the range $0 \leq B \leq 12$ Tesla. The samples were typically irradiated with amplitude-modulated microwaves over the frequency range $27 \leq f \leq 60$ GHz, as a double lock-in technique was employed to extract the microwave induced signal, U_{xx}, that exhibits ESR. For NMR measurements, the specimens were subjected to simultaneous microwave and rf excitation, with the rf spanning the range $30 \leq f \leq 100$ MHz. [17-20]

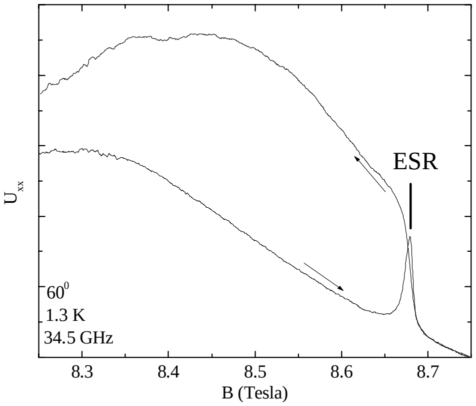

Fig. 4) Sweep direction dependent hysteresis in the vicinity of filling factor $\nu = 3$ at a tilt angle of 60^0 in the ESR signal signifies Dynamic Nuclear Polarization (DNP) via the Overhauser effect.

Figure 2(a) shows the transport response of a device under microwave excitation at 50 GHz. Here, the sample shows typical quantum Hall characteristics as the diagonal resistance R_{xx} exhibits, with increasing B, Shubnikov-deHaas oscillations followed by vanishing R_{xx} over wide B intervals, while the Hall resistance R_{xy} exhibits a linear-in-B increase, with Hall plateaus quantized in units of h/e^2, as expected for

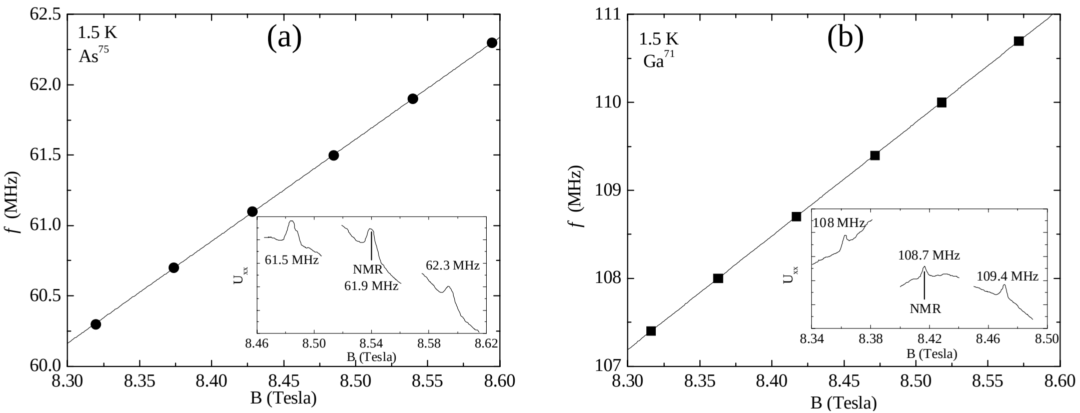

Figure 5) (a) (inset) The electrically detected Nuclear Magnetic Resonance of As^{75} nuclei in a GaAs/AlGaAs device illuminated with 34.5 GHz microwave radiation at a tilt angle of 60^0, with radio frequency radiation as indicated. The main panel shows the linear shift of the NMR frequency with increasing magnetic field. (b) (inset) The electrically detected Nuclear Magnetic Resonance of Ga^{71} nuclei. The main panel shows the linear shift of the NMR frequency with increasing B.

integer quantum Hall effect.[13] In this swept-B experiment, the microwave excitation helps realize a resonance condition, when the photon energy, h*f*, matches the level spacing of the spin split bands, $g\mu_B B$. Such spin resonance leads to a resonant heating of the electron system, which is manifested as a detectable change in the electrical resistance. As illustrated in Fig. 2(a), the microwave induced signal U_{xx}, exhibits such ESR in the vicinity of filling factor $\nu = 1$, for $f = 50$ GHz, when the sample is oriented perpendicular to the magnetic field. Further ESR data are summarized for a number of microwave frequencies in the vicinity of filling factor $\nu=3$ in the inset of Fig. 2(b), as the main panel shows the variation of the electron spin resonance frequency vs. the magnetic field. These data help to demonstrate that electrically detected ESR is readily observable in the quantum Hall limit in fixed–*f*, swept-B measurements. They also confirm good sensitivity and a large signal to noise ratio in the electrically detected ESR signal.

Figure 3 exhibits electrically detected ESR in a complementary fixed magnetic field, swept frequency experiment, which was carried out in order to compare the effectiveness of the experimental approach in the two situations. The fixed-B experimental data shown in Fig. 3(a) indicate non-monotonic, B-insensitive, microwave induced signals U_{xx}, which are attributed to *f*-dependent radiation intensities at the sample. In addition, there is a strong B-sensitive response vs *f*, which is the ESR signal. This feature demonstrates a good signal-to-noise ratio for the electrical detection of ESR even in this complementary fixed-B, swept-*f* measurement scheme. In order to characterize the resonance, the lineshape of the ESR signal at 8.525 T is shown on an expanded scale in Fig. 3(b), along with Gaussian and Lorentzing fits to the data. The fits suggest a line broadening of approximately $\Delta f = 0.06$

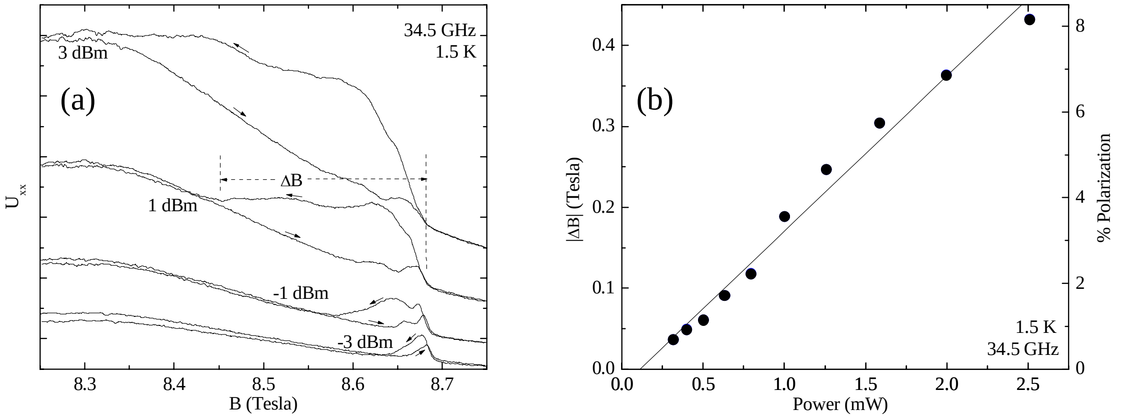

Fig. 6) (a) This figure shows the sweep direction dependent hysteresis in the electrically detected Electron Spin Resonance signal at 34.5 GHz and a tilt angle of 60^0. The hysteresis indicates Dynamic Nuclear Polarization (DNP) via the Overhauser effect and the width ΔB of the down-sweep ESR is a measure of the nuclear polarization. Note the strong dependence of the ΔB on the applied microwave power, in dBm. (b) The width, ΔB, of the ESR on the down-sweep traces from panel (a), is plotted vs. the applied microwave power. ΔB increases approximately linearly with the power. The right axis shows the magnitude of the nuclear polarization.

GHz, which indicates a large inhomogeneous broadenening contribution to T_2^* for electrons.

A role for dynamic nuclear polarization in such experiments can be motivated by exhibiting hysteretic transport in, for example, fixed-*f*, swept-B measurements, of the type shown in Fig. 4. Here, a broad linewidth is observed in the down-sweep measurement because a nuclear magnetic field B_N compensates for the reduced applied magnetic field, and helps to maintain the ESR condition even below the magnetic field where ESR would normally occur. The associated polarization of nuclei can be confirmed by examining the sensitivity of the electrical resistance to nuclear magnetic resonance (NMR). For this purpose, microwave and rf excitation were simultaneously applied to the specimen, with the rf chosen to coincide with the nuclear magnetic resonance frequency of the host nuclei, i.e., Ga or As. The results, illustrated in Fig. 5, confirm that enhanced nuclear polarization is responsible for the hysteretic transport observed in Fig. 4.

Measurements of the type shown in Fig. 4 were examined in detail in order to determine whether the magnitude of the hysteresis, i.e., the nuclear spin polarization, can be controlled by experiment. The results of such studies, illustrated in Fig. 6 (a), show that the hysteresis-magnitude ΔB is a strong function of the incident radiation power. As the width of the down sweep ESR line can be related to the magnitude of the nuclear spin polarization, the observed ΔB have been converted to the polarization factor, as in the right ordinate of Fig. 6(b). The results indicate a substantial increase over the expected nuclear spin polarization at the same temperature, and they suggest the possibility of fully polarizing the nuclear spin system, using this approach, in the quantum Hall regime**.**

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Summary of results (Supplement):

Zero-resistance-states induced by microwave - excitation in GaAs/AlGaAs heterostructures

Vanishing electrical resistance in condensed matter has heralded the birth of new physical phenomena such as superconductivity, which developed from the detection of a zero-resistance-state in a metal below a critical temperature T_C.[1] More recently, the discovery of quantum Hall effects stemmed from investigations of zero-resistance-states at low temperatures and high magnetic fields in the 2-Dimensional Electron System (2DES).[2,3] In quantum Hall systems and superconductors, there is often a correlation between the disappearance of the resistance and the appearance of a gap in the energy spectrum.[1,2,3] The origin of the gap, and the interplay between the gap and physical effects, have served as motivation for much advance in condensed matter physics. Thus, it was a pleasant surprise when this research yielded the discovery of novel zero-resistance-states and perhaps spectral gaps in an unexpected setting - the high mobility two dimensional electron system irradiated by low energy photons.[4]

Briefly, the experiments carried out by Ramesh Mani showed that ultra high mobility GaAs/AlGaAs heterostructures including a 2DES exhibit vanishing diagonal resistance *without Hall resistance quantization*, at low temperatures, T, and low magnetic fields, B, when the specimen is subjected to Electro-Magnetic (EM) wave excitation.[4] Zero-resistance-states occurred about $B = 4/5\ B_f$ and $B = 4/9\ B_f$, where $B_f = 2\pi f m^*/e$, m^* is the electron mass, e is electron charge, and f is the EM-wave frequency, and the resistance-minima followed a series $B = [4/(4j+1)]\ B_f$ with j=1,2,3,… Temperature-dependent measurements on the resistance-minima also demonstrated activated transport indicative of a spectral-gap at the Fermi level.[5] The results pointed out a novel radiation-induced, electronic-state-transition in the GaAs/AlGaAs 2DES.[4]

For these experiments, Hall bars of width w, with $50 \leq w \leq 200\ \mu$m, and square shaped specimens up to ~ 3 x 3 mm^2 were fabricated from ultra high mobility GaAs/AlGaAs heterostructures exhibiting $n(4.2\ K) \cong 3 \times 10^{11}$ cm^{-2} and a mobility $\mu(1.5\ K) \cong 1.5 \times 10^7$ cm^2/Vs. Typically, a specimen was mounted inside a waveguide, immersed in pumped liquid Helium, and irradiated with EM- (micro-) waves over the frequency range $27 \leq f \leq 120$ GHz, at a power level of ≤ 1 mW in the vicinity of the sample.

Fig. 7 (a) shows the diagonal (R_{xx}) and Hall (R_{xy}) resistances measured in the four-terminal configuration using low frequency ac lock-in techniques. Here, R_{xx} and R_{xy} exhibit the usual quantum Hall behavior for $B \geq 0.4$ Tesla at $f = 103.5$ GHz.[2,3] In contrast, at $B < 0.4$ Tesla, see inset, Fig. 7(a), a radiation induced signal occurs and, remarkably, the resistance vanishes over a broad B-interval around B = 0.198 Tesla!

Further high-resolution measurements are shown in Fig. 7 (b). Without EM-excitation, R_{xx} exhibits Shubnikov-deHaas oscillations for $|B| \geq 0.2$ Tesla (Fig. 7 (b)). Radiation induces additional oscillations, which might be attributed to scattering between Landau levels.[6] Yet, the data reveal that, at the minima, R_{xx} falls well below the resistance measured without radiation and it vanishes around $4/5\ B_f$ and $4/9\ B_f$ - magnetic fields set by $B_f = 2\pi f m^*/e$, with $m^* = 0.067m$, the GaAs electron effective mass.[7] Although these zero-resistance-states exhibit a flat bottom as in the quantum Hall regime,[2] R_{xy} does not exhibit plateaus over the same B-interval. A normalized B^{-1} plot (see Fig. 7(c)) demonstrates periodicity in B^{-1} with minima that satisfy $B_{min}^{-1}/\delta = [4/(4j+1)]^{-1}$ with j=1,2,3… Here, δ is the oscillatory period in B^{-1}, which agrees with B_f^{-1}. Notably, half-

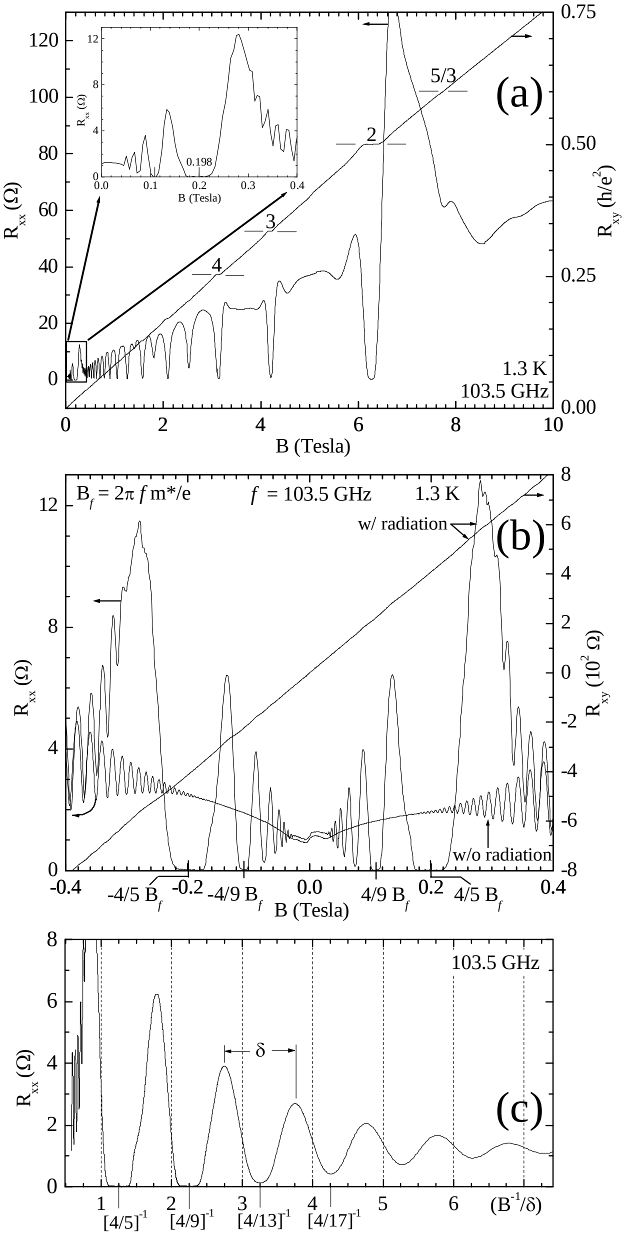

Fig. 7(a): The Hall (R_{xy}) and diagonal (R_{xx}) resistances in a GaAs/AlGaAs heterostructure under excitation at 103.5 GHz. Quantum Hall effects occur at high B as $R_{xx} \rightarrow 0$. (inset): An expanded view of the low-B data showing $R_{xx} \rightarrow 0$ in the vicinity of 0.198 Tesla.

(b): Data over low magnetic fields obtained both with (w/) and without (w/o) radiation at 103.5 GHz. Note the vanishing resistance under radiation in the vicinity of $\pm 4/5\ B_f$ and $\pm 4/9\ B_f$, and the linear Hall effect over corresponding B-intervals. In contrast, quantum Hall systems typically exhibit plateaus in the Hall resistance over the B-intervals where vanishing resistance is observed.

(c): A normalized B^{-1} plot of the low-B data. Resistance minima occur at $[4/(4j+1)]^{-1}$ with j=1,2,3… Here, δ is the oscillatory period in B^{-1}, which agrees with B_f^{-1} within experimental uncertainties (~1%). Note that the j=1 and j=2 states exhibit vanishing resistance.

cycle plots also confirmed a "1/4 cycle phase shift" of the extrema with respect to integral B_f^{-1}, as suggested by Fig. 7(c).

As B_f depends on *f*, the periodicity of these radiation induced magnetoresistance oscillations changed with the microwave frequency, and a given resistance minimum moved to higher B with increasing *f*. Indeed, it was observed that, over a low-*f* range to 40 GHz, R_{xx} exhibited just a minimum at 4/5 B_f. Then, over an intermediate *f*-range to 60 GHz, a zero-resistance-state was first observed at 4/5 B_f . A second zero-resistance-state became evident around B = 4/9 B_f over the highest *f* -range to 120 GHz.

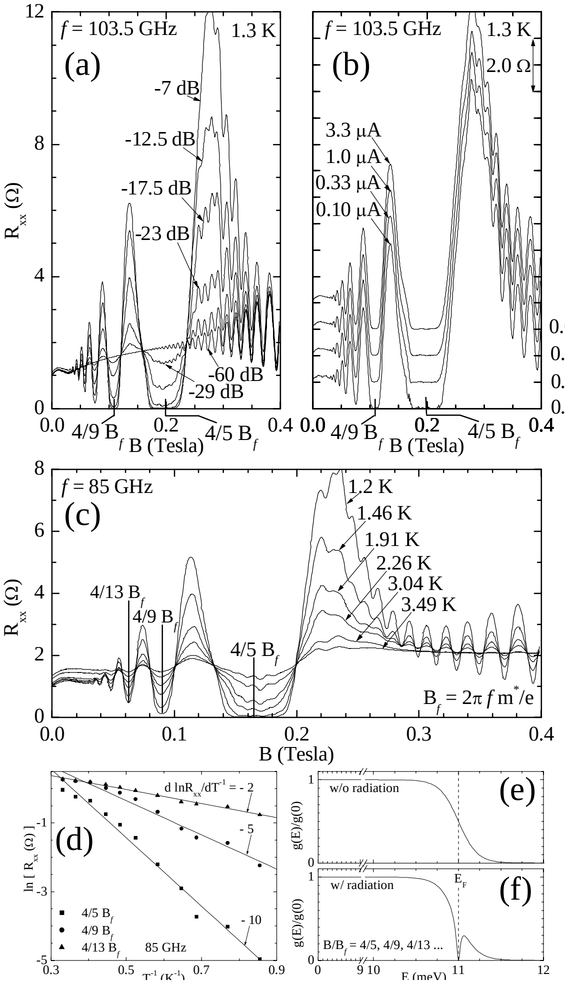

Fig. 8 (a): The amplitude of the radiation induced resistance oscillations increases with increasing power, i.e., attenuation → 0 dB, as the resistance at the minima fall below R_{xx} without radiation, leading to zero-resistance-states at 4/5 B_f and 4/9 B_f.

(b): The lineshape of the radiation induced resistance oscillations is insensitive to the magnitude of the current.

(c): The T-dependence of the magnetoresistance at 85 GHz under constant-power radiation. The radiation induced resistance minima become deeper at lower temperatures. Additional weak resistance oscillations occur about the 4/5 B_f minimum at higher temperatures.

(d): A plot of the natural logarithm of the resistance vs. the inverse temperature, i.e., ln R_{xx} vs. T^{-1}, at B = 4/5 B_f, 4/9 B_f, and 4/13 B_f for the 85 GHz data of panel (c) suggests activated transport and gap-formation.

(e) A sketch of the normalized density of states vs. the energy in the absence of radiation at low B, when Landau level quantization is imperceptible.

(f) A sketch of the effective density of states vs. E at B = (4/4j+1) B_f, with j=1,2,…, when radiation induces a zero-resistance-state. The formation of a gap around E_F is consistent with observed activated transport (see (d)).

Power dependence data of Fig. 8(a) show that as the radiation intensity is increased (i.e., dB -> 0), the resistance at B = [4/(4j+1)] B_f tends to decrease and, at 4/5 B_f and 4/9 B_f, $R_{xx} \rightarrow 0$. The current dependence data shown in Fig. 8(b) demonstrate insensitivity to the current and the Hall electric field. The temperature variation of R_{xx} at 85 GHz, shown in Fig. 8(c), displays both the strong T-dependence of R_{xx} and the low-T requirement for the zero-resistance-state. The T-variation of R_{xx} at the deepest minima suggest *activated transport*, i.e., $R_{xx} \sim \exp(-\kappa/2k_BT)$,[2,5] see Fig. 8(d), and the activation energy exceeds the Landau level spacing.

So far as other scales are concerned, at the B = 0.198 Tesla minimum (see Fig. 7(a)), the cyclotron energy $\hbar\omega_c$ = 0.342 meV is 4/5 of the photon energy hf = 0.428 meV at 103.5 GHz, and the Hall effect implies a filling factor ≅ 63. The transport mean free path is 138 μm for $\mu = 1.5\times10^7$ cm^2/Vs. The transport lifetime, $\tau_t = m^*\mu/e = 5.8 \times 10^{-10}$ s, and the single particle lifetime $\tau_S = \hbar/2\pi k_BT_D = 1.1 \times 10^{-11}$ s, suggest a large ratio, $\tau_t/\tau_S \cong 53$, indicative of mostly small angle scattering.[3] The predominance of small angle scattering, and the large electron mobility are important features in the experiment.

Several other groups have since confirmed these experimental observations.[8-12] At the University of Utah, Zudov et al. confirmed the radiation induced zero-resistance states and the associated large activation energies using samples grown at Bell laboratories.[8] R. L. Willett of Bell Laboratories showed the effect using microwave frequencies as low as 3 GHz.[12] These experimental reports by several groups in quick succession served as the catalyst for a surge in theoretical studies of this novel non-equilibrium effect.[13-27]

Among these theoretical works, J. C. Phillips (Rutgers U.) has suggested that the effect could be a manifestation of a sliding charge density waves.[13] Durst and co-workers invoked an oscillatory density-of-states, an electric field, and impurity scattering in order to identify the radiation induced resistance oscillations with a driven current.[14,17] This theory reproduced the period and the phase reported by Ramesh Mani and coworkers.[4] However, it yielded a negative resistivity for sufficiently large radiation intensities.[14-17] Andreev et al.,[15] and Anderson and Brinkman,[16] suggested a physical instability for the negative resistivity state, while Andreev et al. also inferred a current dependent resistivity and the formation of current domains, and proposed a scenario for realizing macroscopic zero-resistance in measurement.[15] A complementary theory by Shi and Xie,[17,21] which modeled the specimen as a tunnel junction, also realized magnetoresistance oscillations, with a period and phase which were consistent with experiment.[4] This theory suggested, in addition, an N-shape current-voltage (I-V) characteristic for the ZRS.[17] Subsequent theoretical work by Bergeret, Huckestein, and Volkov provided clarification and proposed, in the strong B-field limit, an S-shape I-V characteristic for Hall bar devices and a N-shape I-V characteristic for the Corbino device.[22] Interestingly, Riviera and Schulz have identified a gap forming mechanism that involves the replication of Landau levels in the presence of radiation.[25] Although these theories have made much progress in understanding aspects of experiment, some features such as the observed activated temperature dependence and the formation of a zero-resistance state have yet to be satisfactorily explained, while the ongoing experiments suggest more rich phenomenology in this novel non-equilibrium effect. The widespread interest in this effect led to a write-up in the April 2003 issue of Physics Today.[27]

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(b) Papers published in conference proceedings

1. R. G. Mani, W. B. Johnson, and V. Narayanamurti, Initialization of a nuclear spin system over the quantum Hall regime for quantum information processing, in the Proceedings of 15th International Conference on the Application of High Magnetic Fields in Semiconductor Physics, Oxford, 5-9 August 2002, Institute of Physics Conference Series Number 171, edited by A. R. Long and J. H. Davies (IOP, Bristol, 2003) 1.6.

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(d) Manuscripts submitted, but not published

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