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Nuclear spin based quantum information processing at high magnetic fields

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Abstract

Quantum computers are machines that exploit the quantum mechanical properties of physical systems to realize an exponential speed-up in problem-solving capability compared with existing computers. Existing schemes for the realization of such machines occur in diverse areas such as atomic physics, nuclear magnetic resonance, superconductivity, quantum optics and solid state physics. We are concerned here with the experimental realization of various elements needed for quantum information processing using nuclear spin immersed in a confined electronic system in the quantum Hall regime. Some distinguishing characteristics of this approach include the application of the Overhauser effect for dynamic nuclear polarization at relatively high temperatures, spin measurement using relatively simple electrical detection techniques, spin control with microwave/radio frequency methods, the utilization of the electronic spin exciton as a possible mobile spin transfer mechanism for the eventual realization of a logic gate, and the application of semiconductor technology to device integration. Concepts involved in this approach are also illustrated with experimental results.

(Some figures in this article are in colour only in the electronic version)

1. Background and motivation

Computers are physical devices that transform an 'input' sequence of abstract symbols into an 'output' sequence of abstract symbols under the guidance of an algorithm. Such machines are valued for their ability to find solutions for any instance of a given class of problems for which an algorithm has been found and a program based on the algorithm has been developed. Yet, the existence of an algorithm, a program and a computer, does not necessarily ensure a quick identification of the solution for all instances of the problem, because the computation time typically increases with the size (in number of bits) of the input. For the solution of especially 'difficult' problems, one searches through the class of available algorithms for the best algorithm. These 'best' algorithms are said to be 'fast' or 'efficient' if the time or, equivalently, the number of steps required for executing them increases no faster than as a polynomial function of the size of the input [1]. The factoring of an integer into its primes is an important problem for which there does not yet exist an efficient classical algorithm. It is said that even the fastest classical algorithms require a time period on the order of $O(\exp(\log N)^{1/3}(\log\log N)^{2/3}) \sim 10^9$ years when N, the integer to be factored, is approximately a 10^3 digit number. Indeed, this challenging aspect of the factorization problem has been exploited as a basis for cryptography by some existing public key cryptographic systems, which count upon the virtual impossibility of factoring sufficiently large numbers [1–5]. With growing electronic commerce, such public key encryption systems are finding widespread application in financial transactions. Yet it is not clear whether these encryption systems will remain secure into the future in the light of advances in quantum computing [1–26].

The fundamental unit of the quantum computer, the quantum bit or 'qubit', is constituted from a two-state system and it includes two basis states, labelled $|1\rangle$ and $|0\rangle$, which are analogous to the 'bit' states of the classical computer. Yet the quantum character makes possible new qubit superposition states, such as $\alpha|1\rangle + \beta|0\rangle$, where α and β are complex amplitudes, which do not have an analogue in the classical bit. This possibility for state superposition at the qubit stage in the quantum computer leads, at a higher level, to the prospect of superposition in computational paths, and a massive parallel computer [1–8]. Special features of quantum systems such entanglement, quantum interference and superposition have been examined recently in order to look for fresh solutions to intractable classical computing problems, and this search has resulted in, for example, a new factorization algorithm [9], which utilizes exponentially fewer computational steps than the best classical algorithm. The identification of this method has pointed out that algorithms exploiting the quantum mechanical characteristics of physical systems can be much more powerful and efficient than those based on classical computing [9, 10], and this has naturally expanded interest in this field [1–26].

Given this strong motivation for developing quantum computers, there has been much recent interest in identifying systems and designs that might be useful in realizing such machines. In particular, there is a need to identify properties of physical systems that might serve as qubits and to study these properties in some detail in order to

(a) clarify their suitability for quantum information storage and
(b) determine associated dynamics that could be utilized in elementary qubit operations.

It also seems necessary to develop and refine an array of measurement tools that could be useful for qubit operations in the system of interest. The scheme of choice should also be amenable, in the end, to 'large-scale integration' so that one is able to construct a machine with a sufficient number of qubits, in the range of 10^3–10^6 [2], to perform a useful calculation.

Among existing scenarios, quantum computing with cold ions confined in a linear trap and interacting with laser beams, considered by Cirac and Zoller [11], has advanced rapidly [11–13]. Turchette *et al* [14] exploited optical nonlinearities in cavity quantum electrodynamics to modify the polarization of a transmitted probe beam via the circular birefringence of an atom coupled to a optical resonator. This approach included the possibility of constructing quantum gates [14, 15]. Chuang *et al* followed the idea of quantum computing using nuclear magnetic resonance (NMR) techniques applied to nuclear spins in ordinary liquids [16], and reported an experimental implementation of Grover's search algorithm [10]. There also exists an exotic scheme for quantum computing using electrons trapped on the surface of helium [17].

In existing classical computers, scaling up to a large number of bits has already been realized through miniaturization and device fabrication on semiconductors by lithography. The existence of this mature technology therefore identifies at least one benefit for semiconductor quantum computing: there is the possibility of adopting existing integration technology for the new computers, instead of developing new technology at additional expense [18]. A semiconductor quantum computing scheme could also lead to a hybrid machine, where a few-qubit quantum computer sitting alongside a classical computer might apply efficient quantum algorithms as needed and feed the results to its classical counterpart, or allow its classical counterpart to preprocess a problem before tackling it. For the sake of compatibility with existing computers in such hybrids, it also appears desirable to search for approaches that exploit electrical effects to measure, and control the interaction between, qubits.

Semiconductor spin based solid state quantum computers, which may be broadly grouped into nuclear spin quantum computers and electron spin quantum computers [18–24], suggest the possibility of realizing a number of these desired characteristics. Associated schemes include:

(a) An early theoretical proposal for nuclear spin quantum computing by Privman *et al*, which identified nuclear spins in quantum Hall systems as qubits [20], and exploited an impurity-mediated two-qubit interaction as the medium for realizing a universal quantum logic gate [20, 21]. In this scheme [20], measurement relied upon the detection of the spin polarization in currents directed across qubit replicas, while logic control relied upon precise, local modification of the impurity state. Notably, this theoretical proposal raised a number of spin measurement and control issues that needed to be addressed by experimenters.
(b) A scheme by Kane for nuclear spin quantum computing in the canonical semiconductor Si [18], which identified the possibility of
    (i) gate-controlled single nuclear spin rotation through the regulation of the overlap between the donor electron and the nucleus in P-doped silicon,
    (ii) gate-controlled two-qubit interaction by electronic spin exchange, and
    (iii) state readout by capacitive detection of the current associated with charge transfer between a pair of donors depending upon the state of the nuclear spin qubits [18].

    Here, device implementation requires precise atomic control in the placement of donor atoms within the Si host, and the subsequent registry of narrow gates for single-donor control.
(c) A plan by Loss and DiVincenzo for electron spin quantum computing using single electron quantum dots, which invokes ferromagnetic quantum dots for state preparation, gate-controlled dot overlap for transient two-qubit interactions, and qubit state measurement by gate-controlled tunnelling into a supercooled paramagnetic quantum dot or spin valve-controlled tunnelling into a single-electron quantum dot electrometer [22].
(d) A method for donor-atom electron spin quantum computing in Si/Ge through g-factor engineering [23]. This approach applies gate control to tune the donor electron resonance frequency, and realizes two-qubit interaction through the gate-controlled overlap of the electronic wavefunction on neighbouring sites. State readout requires that the charge state of the donor (D^0, D^+, D^-) modulate a 'channel' current in a conducting plane.
(e) A scheme for an all-silicon quantum computer, where nuclear spin of ^{29}Si qubits are arranged as chains on a spin-zero silicon matrix [24].

The phase coherence time, t_ϕ, the time for carrying out a single-qubit operation, t_{switch}, and the ratio t_ϕ/t_{switch}, which determines the number of operations that can be carried out in a time period t_ϕ, can be used to compare the relative merits of electron spin quantum computers and nuclear spin quantum computers [2, 6]. Estimates suggest that as many as 10^7 operations can be carried out in nuclear spin quantum computers versus only 10^4 operations in electron spin quantum computers, before the loss of quantum coherence. This point, and the long nuclear spin coherence time [2], identify a special simple advantage for nuclear spin quantum computing over electron spin quantum computing: nuclear spins allow more time for the experimenter to carry out qubit manipulations. However, this advantage for nuclear spin quantum computing is countered by the shortcoming that comes with the small energy scales of nuclear spins, namely the need to work at extremely low temperatures, T, and high magnetic fields, B.

The hybrid scheme examined here aims to overcome this shortcoming of nuclear spin based quantum information systems by applying the Overhauser effect in the quantum Hall regime to realize large nuclear polarizations at relatively high temperatures [25–28]. Thus, this novel approach attempts to combine the favourable timescales of nuclear spins with the large energy scales of the electronic spin system [25]. The nuclear spin state is also to be detected by examining the influence of the associated magnetic field on electron spin resonance (ESR) [25, 29, 30]. Finally, an electronic spin exciton is to be tested as a possible mobile spin transfer mechanism that could be useful for the realization of two-bit logic [25, 31]. The associated experimental effort therefore focuses upon microwave/radio frequency (rf) spin manipulation and electrical detection of ESR and NMR in semiconductor nanostructures to set, measure and operate on nuclear spin [25, 26, 29, 30]. This approach could lead to a future electrical resistance-readout, electric-control, microwave/rf-write, semiconductor-based nuclear spin quantum computer.

2. Nuclear spin manipulation in the quantum Hall regime

The quantum Hall regime is the regime of interest here because

(a) the spin splitting of electronic states can then lie in the energetically accessible microwave region,
(b) microwave-induced electronic spin–flip transitions can be detected electrically by monitoring the four-terminal resistance,
(c) spin decay of electrons can lead to the spin polarization of nuclei within the extent of the electronic wavefunction via the flip-flop, electron–nuclear hyperfine interaction,
(d) the nuclear spin state can be electrically characterized by observing the Overhauser shift in ESR, and
(e) the nuclear spin relaxation time is sufficiently long ($\sim 10^3$ s) to allow well paced, deliberate measurements [29, 30].

The two-dimensional electron gas (2DEG) obtained in the GaAs/AlGaAs semiconductor system is well suited for the initial studies because it readily exhibits the quantum Hall effect (QHE), an effect that is characterized by vanishing diagonal resistance ($R_{xx} \to 0$) and the quantization of the Hall resistance in units of h/e^2, in the vicinity of integral filling factors [28]. The suppression of electronic scattering under QHE conditions in this system also leads to long nuclear spin relaxation and decoherence times, and helps to realize a system where nuclear spin dynamics are dominated by coherent spin exchange via electrons [20], a phenomenon which can be used to construct an electrically switchable qubit interaction and two-qubit logic function. In addition, electrical detection of ESR and NMR are known to offer spin detection sensitivity in this 2DEG that includes few nuclei and electrons in comparison to traditional bulk, three-dimensional systems [29, 30, 32, 33].

The physical effect of interest for quantum information processing is the hyperfine interaction which couples the electronic and the nuclear spins via a Hamiltonian of the form $H = g_e\mu_B \boldsymbol{B}\cdot\boldsymbol{S} + g_n\mu_n\boldsymbol{B}\cdot\boldsymbol{I} + A\boldsymbol{I}\cdot\boldsymbol{S}$ [27, 34]. Here, $\boldsymbol{B}$ is the magnetic field, $\boldsymbol{S}$ is the electronic spin, $\boldsymbol{I}$ is the nuclear spin, g_e is the electronic g-factor, g_n is the nuclear g-factor, $\mu_B = qh/4\pi m_e$ is the Bohr magneton, $\mu_n = qh/4\pi M$ is the nuclear Bohr magneton and A is the hyperfine interaction constant. The electron–nuclear coupling term, which may be rewritten as $A\boldsymbol{I}\cdot\boldsymbol{S} = A((I_+S_- + I_-S_+)/2 + I_zS_z)$, suggests that electronic spin relaxation in this system can occur through the coherent 'flip-flop' type (I_+S_- or I_-S_+) exchange of spin with the nucleus. This implies that ESR carried out in a 2DEG can dynamically polarize the nuclei that lie within the extent of the electronic system. Physically, the process consists of a microwave-induced transition of the electron from one spin state to another. As the excited spin electron relaxes back to the lower-energy spin state, it trades its surplus spin with a nearby nucleus resulting in a change in the nuclear spin. Dynamical nuclear polarization implies, however, that ESR cannot be maintained indefinitely at the fixed microwave frequency in a constant magnetic field because the nuclei create an additional effective magnetic field B_N that produces a back-action on the electronic spin splitting, which tends to shift the ESR. Here, the sign of both the g-factor of the electrons and the nuclei determines the relative orientation of the nuclear magnetic field B_N with respect to the applied magnetic field. In the GaAs/AlGaAs system, experiment has shown that the B_N serves to increase the electronic spin splitting, i.e., $E_S = g\mu_B(B + B_N) > g\mu_B B$, above the 'bare' spin splitting energy, $g\mu_B B$ [29]. In this situation, the equality $g\mu_B(B + B_N) = hf$ can be maintained only by slowly reducing the applied magnetic field, B, in order to compensate for the continual increase in B_N. As this magnetic field 'Overhauser' shift of the ESR correlates with the polarization of the nuclei, ESR can be used to both set and measure the state of nuclear spin: the nuclear polarization can be set by maintaining ESR while down-sweeping the magnetic field. The nuclear polarization can then be ascertained by measuring the magnetic field value at which ESR becomes possible on a subsequent up-sweep of the magnetic field. Thus, the magnitude of B_N reflects the magnitude of the nuclear polarization. Note that nuclear polarization can be deliberately destroyed, if necessary, by applying a saturating rf wave with its magnetic vector perpendicular to the quasi-static dc magnetic field. This NMR effect can also be detected electrically via a measurement of the resistance in the quantum Hall system.

The presence of a mobility gap near integral filling factors in a quantum Hall system leads to quasi-dissipationless transport, a long electronic mean free path, and protracted nuclear spin relaxation and decoherence times. Under such

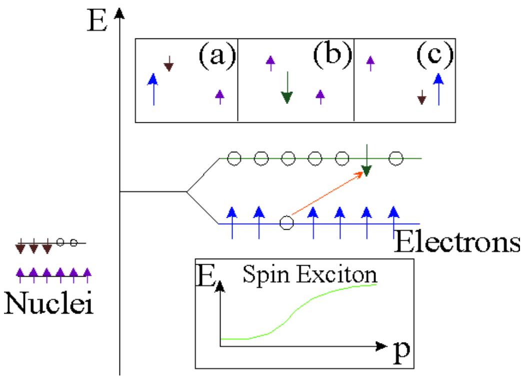

Figure 1. Centre: flipping an electron spin creates a spin exciton, which is a propagating elementary excitation [31]. Bottom: the spin exciton dispersion relation. Top: Illustration of nuclear polarization transfer (swap operation) mediated by a spin exciton. (a) The initial state. (b) Left nucleus transfers its polarization to an electron through the creation of a spin exciton. The spin exciton propagates towards the right nucleus. (c) The final state. The spin exciton vanishes after transferring its polarization to the right nucleus, bringing the electron back to its ground state.

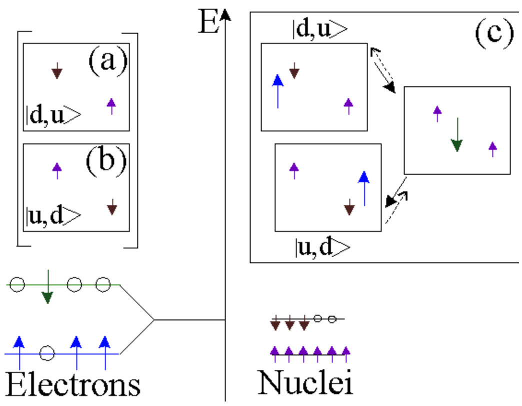

Figure 2. The figure depicts a semiclassical illustration of superposition based on the exchange of spin excitons. (a) A state with the left nucleus in the 'down' orientation and the right nucleus in the 'up' orientation. (b) A complementary state with the left nucleus in the 'up' orientation and the right nucleus in the 'down' orientation. A two-nucleus system that coherently coexists in both the (a) and (b) states is similar to quantum mechanical superposition and (c) shows this possibility via the exchange of spin exciton. (c) The 'd' nucleus in the $|d, u\rangle$ state can exchange spin with a 'up' electron and create a spin exciton, which propagates to the right and flips the spin of the right nucleus, thereby realizing the $|u, d\rangle$ state. This process is shown by the bold arrow connecting the $|d, u\rangle$ and the $|u, d\rangle$ states via the intermediate state. The dashed arrow illustrates the inverse process.

conditions, the coherent transfer of the spin polarization of nuclear spins by electrons becomes possible through the creation of spin excitons (see figure 1) [20, 31]. By utilizing this spin exciton mechanism, a nucleus can transfer its polarization to a distant nucleus, forming a semiclassical analogue of a superposition state, as depicted in figure 2. Here, a spin exciton propagating to the right converts the $|d, u\rangle$ state to the $|u, d\rangle$ state, while a counter-propagating (left-moving) spin exciton converts the $|u, d\rangle$ state back to the $|d, u\rangle$ state. Thus, in a confined system consisting of a pair of nuclear spins and a spin exciton, the nuclear system oscillates between the $|d, u\rangle$ and the $|u, d\rangle$ states, similar to quantum superposition. These depictions (figures 1 and 2) indicate that, in a quantum Hall system, both the transfer of spin polarization of nuclear spins and the superposition of nuclear spin states can be carried out by quantum Hall electrons dressed as spin excitons. This important role for electrons as messengers identifies the possibility for electric control in a nuclear spin quantum Hall quantum information-processing scheme. Here, directed transport of spin polarization might be realized, when necessary, by applying and setting the direction of a current.

Figure 3 illustrates a candidate structure for examining nuclear polarization transfer via electrons in future experiments; this is not the device structure that will be examined in the experimental portion of this paper [25, 26]. The device of figure 3 may be viewed as a quantum wire pair with a barricade. Here, we imagine two long parallel wires fabricated from a GaAs/AlGaAs heterostructure with a gate-controlled barrier G_B running lengthwise between them. Two other gates G_1 and G_2 might serve to vary individually the electronic density in each wire. For simplicity other gates, which would serve to isolate the wires from the contacts (and the external world) during wire–wire interaction, are not shown here. An experiment might proceed as follows:

(1) Erect a barrier between the two wires by applying a suitable voltage on G_B.

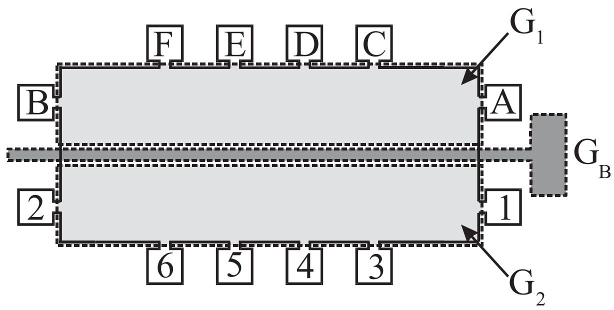

Figure 3. Schematic of a quantum wire pair with a barricade. Here, two wires, one each at the top and bottom, can be electrically merged or separated with the aid of an electrically tunable gate barrier, G_B. Each wire can be measured separately using associated contacts that have been labelled alphabetically (A–F) or numerically (1–6). The electron density in the top (bottom) wire can be changed using gate $G_1 (G_2)$.

(2) Deplete one of the wires, say wire 2, by applying a suitable voltage on G_2 so that there are no free electrons within it.

(3) Sweep the quasi-static magnetic field to a high value such that the Fermi level in wire 1 lies in the spin split gap corresponding to, say, filling factor 1 [34]. Experimental conditions are such that the longitudinal resistance exhibits a Shubnikov–de Haas resistance minimum. Upon verifying this feature,

(4) Perform ESR in this vicinity by suitable microwave illumination on wire 1 and detect ESR through a measurement of the four-terminal resistance of wire 1. Then:

(5) Carry out ESR with a slow down-sweep of magnetic field to dynamically polarize nuclei in wire 1. Here, one might characterize nuclear spin relaxation lifetime in wire 1.

(6) Maintain the barrier due to gate G_B between the wires but introduce electrons into wire 2, at the same density as wire 1, by adjusting the gate voltage G_2.
(7) Remove the barrier between the wires and let the electronic wavefunction spread over both wires for some period of time. Adjust conditions to ensure the flip-flop transfer of nuclear spin polarization onto electrons in wire 1, followed by a flop-flip spin exchange in wire 2 that transfers electronic spin polarization onto nuclei in wire 2.
(8) Erect the barrier between the wires once again and carry out ESR on wire 2 to determine the nuclear polarization transfer into wire 2.
(9) Characterize the polarization transfer. Such a study would yield physical parameters which are essential for designing a multi-qubit device [25, 26, 36].

The integration of the above-mentioned physical phenomena and measurement/control schemes into a quantum information processor ought to be consistent with the criteria listed in [6]. According to DiVincenzo *et al* [6] realization of a quantum computer requires five essential components:

(i) the machine should have a collection of bits,
(ii) it should be possible to set all the memory bits to 0 before the start of each computation,
(iii) the error rate should be sufficiently low,
(iv) it must be possible to perform elementary logic operations between pairs of bits, and
(v) reliable output of the final result should be possible [2].

In our approach, nuclear spin serves as the information storage medium and, ultimately, nuclear spin in a wire or a dot will serve as the qubit. Here, a regular array of qubits could be realized by ion implantation of a nuclear spin active species into a nuclear spin inactive host. Nuclear spin initialization is to be achieved at a high temperature by utilizing the Overhauser effect [27]. With this effect, it should, in principle, be possible to achieve a nuclear polarization ratio roughly on a par with the electron polarization ratio at the same temperature. This typically corresponds to an enormous boost in the nuclear polarization and makes viable the operation of a solid state nuclear spin computer at a relatively high (liquid helium) temperature. Thus, the writing, say, of a '1' state on a qubit 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 an rf π-pulse that rotates the spins by 180°. A local operation on nuclear spin can be implemented by introducing or removing electrons into the nuclear neighbourhood using a voltage-controlled 'gate', as the specimen is irradiated with microwaves. The nuclear spin remains unaffected by the radiation if free electrons do not occur around the nuclear spin 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 qubit to a '1' state and then subjecting it to a resonant rf $\pi/2$ pulse that 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. Present theoretical understanding of the spin–spin interaction of two nuclei, labelled 1 and 2, coupled by spin exciton exchange, suggests that the effective Hamiltonian, is proportional to $I_{1+}I_{2-} + I_{2+}I_{1-}$, where $I_{\pm}$ are the raising and lowering operators for the appropriate nuclear spins [20, 31, 37]. The quantum controlled-NOT two-qubit function, which is a function that operates on two qubits and leaves the second qubit unchanged if the first is '0', and flips the second qubit ('1' → '0' or '0' → '1') if the first qubit is in the '1' state, can be constructed from this type of interaction and single-qubit rotations [38].

3. Experiment

Our experiments have examined the electrical response of GaAs/AlGaAs heterostructure devices under simultaneous microwave (27 GHz $\leqslant f \leqslant$ 60 GHz) and rf (30 MHz $\leqslant f \leqslant$ 100 MHz) excitation, over the range 1.2 K $\leqslant T \leqslant$ 4.2 K and $B \leqslant$ 12 T. Results are shown here in order to illustrate the concepts and demonstrate the viability of the scheme discussed above.

Figure 4 shows the transport response of a device under microwave excitation at 50 GHz. Here, the diagonal resistance R_{xx} exhibits Shubnikov–deHaas oscillations with increasing B and vanishing R_{xx} over wide B intervals, while the Hall resistance R_{xy} exhibits a linear-in-B increase and quantization (in units of h/e^2), as expected for integer QHE [28]. Also shown in the figure is the microwave-induced ESR in the vicinity of filling factor $\nu = 1$ that is detected using a dual lock-in technique. Here, one observes a large sharp resonant response in the data, which demonstrates a good signal to noise ratio.

The experimental signature of dynamic nuclear polarization (DNP) due to the Overhauser effect is shown in figure 5 for a quantum Hall system in the vicinity of $\nu = 3$ at a tilt angle $\theta = 60°$. Here, the sample has been tilted with respect to the external field in order to bring an integer QHE state into the magnetic field interval over which ESR could be observed with a specific microwave source spanning a narrow frequency interval. Note that the microwave-induced voltage shows a narrow resonance on the up-sweep of B, signifying ESR. However, on the B down-sweep, one observes large hysteresis because polarized nuclear spins contribute a magnetic field B_N that helps to preserve the ESR condition $E_S = g\mu_B(B+B_N)$ over a broad B-interval. These data demonstrate the good signal-to-noise ratio and the good sensitivity to nuclear spin polarization that can be obtained in such experiments.

The suggested role for nuclei in such hysteretic transport (figure 5) can be confirmed by attempting to change the nuclear polarization by NMR over the hysteretic region [29]. For this purpose, measurements were carried out with simultaneous microwave and rf irradiation of the specimen, with the rf chosen to coincide with the NMR frequency of the host nuclei, i.e. Ga or As. The results of such experiments, which sought to detect NMR of the ^{69}Ga nuclei, are illustrated in figure 6. The inset of this figure shows the down-sweep electrical response of the specimen with rf radiation at 85, 85.5, and 86 MHz, respectively. The observation of resonance in figure 6 confirms

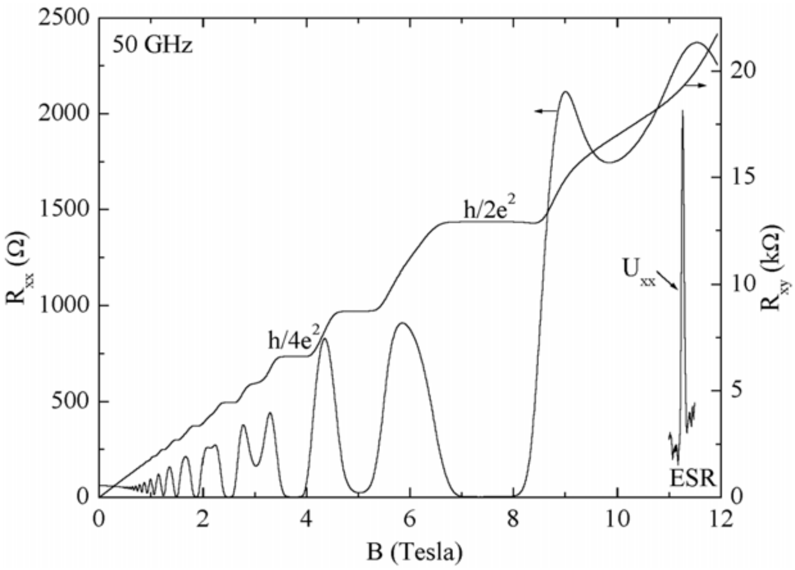

Figure 4. The plot shows the transport characteristics of a GaAs/AlGaAs device under microwave excitation over the quantum Hall regime. The microwave-induced voltage U_{xx} shows ESR.

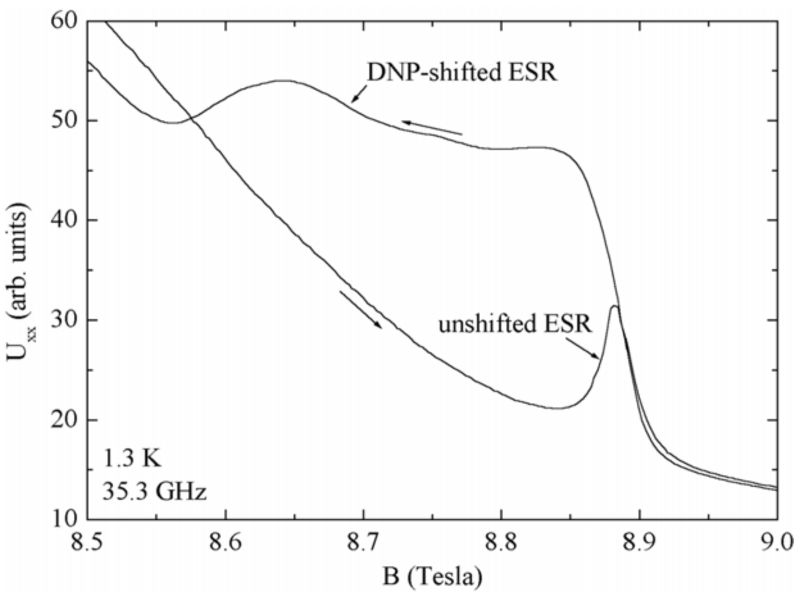

Figure 5. Sweep direction-dependent hysteresis in the electrically detected ESR signal at 35.3 GHz using a double modulation technique indicates DNP via the Overhauser effect. The specimen was tilted at an angle of 60° with respected to the static magnetic field.

that dynamical nuclear polarization is responsible for the observed hysteretic transport (see figure 5).

The magnitude of the nuclear spin polarization in the experiment of figure 5 can be estimated by taking into account the contributions of the elemental components ^{69}Ga ($I = 3/2$), ^{71}Ga ($I = 3/2$) and ^{75}As ($I = 3/2$), which provide field shifts $B_N^{69\mathrm{Ga}} = -0.91\ \mathrm{T}\langle I^{69\mathrm{Ga}}\rangle$, $B_N^{71\mathrm{Ga}} = -0.78\ \mathrm{T}\langle I^{71\mathrm{Ga}}\rangle$, and $B_N^{75\mathrm{As}} = -1.84\ \mathrm{T}\langle I^{75\mathrm{As}}\rangle$ respectively. Thus, in this instance (figure 5), the data suggest that about a tenth of the nuclei have been polarized at 1.3 K, which constitutes a substantial increase over the expected nuclear polarization at the same temperature based on thermal equilibrium estimates.

These studies have shown that the nuclear spin polarization realized utilizing the Overhauser effect depends sensitively upon the temperature, the sweep rate and the microwave intensity. And they suggest that an appropriate combination of these parameters can serve to help fully polarize a nuclear spin system in the quantum Hall regime at liquid helium temperatures. Once the nuclei have been initialized, then the long lifetimes of nuclei might be exploited to carry out, at a deliberate pace, pulse rf-based nuclear spin manipulations, before state readout.

4. Summary

A possible approach to manipulate, measure and control nuclear spin immersed in a confined electronic system in the quantum Hall regime has been examined here as a special example of the spin-based solid state quantum-computer paradigm. Some distinguishing characteristics of

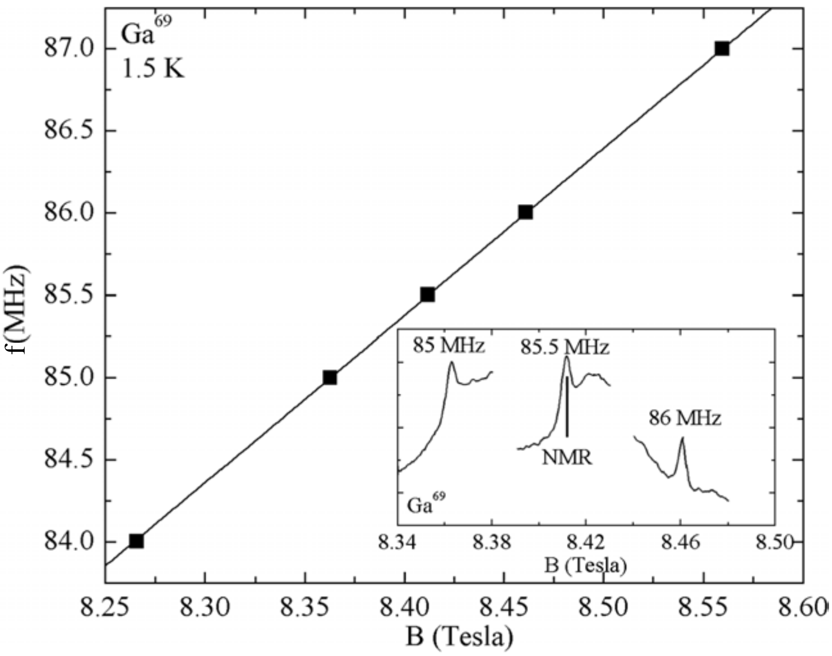

Figure 6. Inset: the electrically detected NMR of ^{69}Ga nuclei in a GaAs/AlGaAs device illuminated with 34.5 GHz microwave radiation at a tilt angle of 60° and rf radiation as indicated. The main panel shows the linear shift of the NMR frequency with increasing magnetic field.

this approach include the application of the Overhauser effect for dynamic nuclear spin polarization, spin measurement using relatively simple electrical detection techniques, spin control with microwave/rf methods, the utilization of the electronic spin exciton as a possible mobile spin transfer mechanism for the eventual realization of a logic gate, and the application of semiconductor technology for device integration. Some concepts involved in this approach were also illustrated with experimental results. Such a scheme might serve to realize an information processor that exploits quantum mechanical properties to realize an exponential speed-up in computing capability compared with existing computers.

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References

[1] Ekert A and Jozsa R 1996 *Rev. Mod. Phys.* **68** 733
[2] DiVincenzo D P 1995 *Science* **270** 255
[3] Bennett C H 1995 *Phys. Today* **48** 24
[4] Brown J 1994 *New Sci.* **133** 21
[5] Grover L K 1998 *Science* **280** 5361
[6] DiVincenzo D P, Burkhard G, Loss D and Sukhorukov E V *Preprint* cond-mat/9911245
[7] Lloyd S 1993 *Science* **261** 1569
[8] DiVincenzo D P, Bacon D, Kempe J, Burkhard G and Whaley K B 2000 *Nature* **408** 339
[9] Shor P W 1994 *Proc. 35th Annual Symp. on the Foundations of Computer Science* ed S Goldwasser (Los Alamitos, CA: IEEE Computer Society Press) p 124
[10] Grover L K 1997 *Phys. Rev. Lett.* **79** 325
[11] Cirac J I and Zoller P 1995 *Phys. Rev. Lett.* **74** 4091
[12] Cirac J I and Zoller P 2000 *Nature* **404** 579
[13] Kielpinski D, Monroe C and Wineland D J 2002 *Nature* **417** 709
[14] Turchette Q A, Hood C J, Lange W, Mabuchi H and Kimble H J 1995 *Phys. Rev. Lett.* **75** 4710
[15] Hood C J, Lynn T W, Doherty A C, Parkins A S and Kimble H J 2000 *Science* **287** 1447
[16] Chuang I L, Gershenfeld N and Kubinec M 1998 *Phys. Rev. Lett.* **80** 3408
[17] Platzman P M and Dykman M I 1999 *Science* **284** 1967
[18] Kane B E 1998 *Nature* **393** 133
[19] Bowden C M and Pethel S D 1999 *Preprint* quant-ph/9912003
[20] Privman V, Vagner I D and Kventsel G 1998 *Phys. Lett.* A **239** 141
[21] Mozyrsky D, Privman V and Glasser M L 2001 *Phys. Rev. Lett.* **86** 5112
[22] Loss D and DiVincenzo D P 1998 *Phys. Rev.* A **57** 120
[23] Vrijen R, Yablonovitch E, Wang K, Jiang H W, Baladin A, Roychowdhury V, Mor T and DiVincenzo D P 2000 *Phys. Rev.* A **62** 012306
[24] Ladd T D, Goldman J R, Yamaguchi F, Yamamoto Y, Abe E and Itoh K M 2002 *Phys. Rev. Lett.* **89** 017901 and references therein
[25] Mani R G *et al* 2000 unpublished
[26] Mani R G, Johnson W B, Narayanamurti V, Privman V and Zhang Y H 2002 *Physica* E **12** 152
[27] Overhauser A W 1953 *Phys. Rev.* **91** 476
Overhauser A W 1953 *Phys. Rev.* **92** 411
[28] Prange R E and Girvin S M (ed) 1990 *The Quantum Hall Effect* (Berlin: Springer)
[29] Dobers M, Klitzing K von, Schneider J, Weimann G and Ploog K 1988 *Phys. Rev. Lett.* **61** 1650
Dobers M 1987 *Dr rer. nat. Thesis* Universität Stuttgart
[30] Berg A, Dobers M, Gerhardts R R and Klitzing K von 1990 *Phys. Rev. Lett.* **64** 2565
[31] Bychkov Yu A, Maniv T and Vagner I D 1995 *Solid State Commun.* **94** 61
[32] Dixon D C, Wald K R, McEuen P L and Melloch M R 1997 *Phys. Rev.* B **56** 4743
[33] Kronmüller S, Dietsche W, Klitzing K von, Denninger G, Wegscheider W and Bichler M 1999 *Phys. Rev. Lett.* **82** 4070

[34] Tannoudji C C, Diu B and Laloe F 1977 *Quantum Mechanics* vol 2 (New York: Wiley) ch XII

[35] Mani R G, Klitzing K von and Ploog K 1992 *Phys. Rev.* B **46** 9877
Mani R G, Klitzing K von and Ploog K 1993 *Phys. Rev.* B **48** 4571
Mani R G, Klitzing K von and Ploog K 1995 *Phys. Rev.* B **51** 2584

[36] Shlimak I, Safarov V I and Vagner I D 2001 *J. Phys.: Condens. Matter* **3** 6059

[37] Mozyrsky D, Privman V and Vagner I D 2001 *Phys. Rev.* B **63** 085313

[38] Imamoglu A, Awschalom D D, Burkard G, DiVincenzo D P, Loss D, Sherwin M and Small A 1999 *Phys. Rev. Lett.* **83** 4204