Physica E 12 (2002) 152–156

PHYSICA E

Nuclear spin based memory and logic in quantum Hall semiconductor nanostructures for quantum computing applications

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Abstract

A hyperfine interaction based approach for setting, measuring, and erasing nuclear polarization in quantum Hall nanostructures is developed for the realization of nuclear spin devices for quantum computing applications.

PACS: 03.67.Lx; 73.43.fj; 76.60.−k; 73.23.−b

Keywords: Quantum Hall effects; Quantum computing; Nuclear spin; Memory; Logic

1. Introduction

The advance of semiconductor technology over the last four decades is often represented by Moore's law which predicted the approximate doubling of switches or transistor devices in an integrated circuit nearly every 18 months. The associated exponential increase in computing power with time was a direct consequence of the reduction in feature size and increased functionality with each succeeding device generation. Although further advances are not expected to be realized easily or inexpensively, the success of the law in describing past technological advance makes it instructive to consider its prediction for the future: within the next two decades, feature size in semiconductor devices could extend below atomic dimensions. This vision of the future, with predicted feature size approaching a physical limit, suggests research into the utilization of the smallest unit of matter in crystalline systems, the nucleus, for device applications ranging from memory cells to logic devices [1,2]. Here, we address the problem of developing an alternative nuclear spin based technology in semiconductors that could lead to nuclear spin memory and logic by the time when most known CMOS technological capabilities will be approaching or have approached their limits as set forth in The International Technology Roadmap for Semiconductors [3].

Atomic nuclei arranged on a lattice can be used for information storage when there is little direct interaction between nuclear spins because one can associate each spin state of, for example, a spin-$\frac{1}{2}$ nucleus with a particular logic state and store a bit of

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information per nucleus by selecting its polarization. With the appropriate choice of physical parameters, the spin relaxation time can be quite long and this can help to realize a non-volatile memory capable of storing information even in the absence of power. In crystalline semiconductors, utilization of the nucleus at each lattice site for information storage can yield very high storage densities, with as many as 10^9 bits in a $0.1\ \mu\text{m} \times 0.1\ \mu\text{m} \times 0.1\mu\text{m}$ sized device [1]. Further, one can imagine engineering the nuclear-spin density as desired, by using epitaxial crystal growth techniques, to construct a superlattice of active nuclear spins in a crystalline host of spin-inert nuclei.

A difficulty to overcome on the path to future solid-state nuclear spin devices is the dearth of techniques for locally manipulating and measuring nuclear spins. Hence, our purpose is to develop the tools necessary to handle and measure small collections of nuclear spins. Another difficulty is the limited knowledge of the electronic–nuclear interaction in low dimensional nanostructures. Thus, we aim to measure and model physical phenomena and relaxation times in such devices. A third goal is to construct nuclear spin memory cells, and realize a controlled-NOT gate which could be useful in quantum computing applications [2].

2. Approach

We apply electrical detection of electron spin- and nuclear magnetic-resonance, and microwave/radio frequency manipulation of nuclei in semiconductor nanostructures to set, measure, and operate on spins that could constitute a memory cell or a logic gate.

The quantum Hall regime is the regime of interest here [4–12] 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 by monitoring the electrical resistance, (c) spin decay of microwave excited electrons leads to the nuclear spin polarization within the extent of the electronic wavefunction via the flip–flop, electronic–nuclear hyperfine interaction, (d) nuclear spin polarization leads to giant, observable Overhauser shift in ESR, and (e) the nuclear spin relaxation time is sufficiently long (10^3–10^4 s) to allow deliberate measurements [6–8].

Electrical methods for electron spin resonance (ESR) and nuclear magnetic resonance (NMR) detection, denoted EDESR and EDNMR, can serve as a basis because they provide spatial resolution, even where traditional bulk techniques turn out to be inadequate, in examining low dimensional systems that include few electrons and nuclei. In EDESR, a measurement is carried out over the QHE regime of the electrical resistance of a semiconductor nanostructure, as microwaves illuminate the sample. Under resonance conditions where microwave energy hf equals E_S, the spin splitting, the enhanced scattering of electrons leads to a resonant increase in the four terminal resistance. NMR can also be detected electrically (EDNMR) when radio frequency (RF) waves are applied to the specimen [6,7].

The physical effect responsible for polarizing nuclei is the hyperfine interaction [5–9]. This electronic–nuclear interaction term allows electronic spin relaxation in this system to occur through the coherent 'flip–flop' type exchange of spin with the nucleus. And, so long as ESR is maintained, the decay of spin-excited electrons continues to increase the average polarization $\langle I \rangle$ of the nuclei. This also produces an additional effective magnetic field B_N that modifies the electronic spin splitting, i.e., $E_S = g\mu_B(B + B_N)$. Thus, the equality $g\mu_B(B + B_N) = hf$, i.e., ESR, can be maintained only by slowly reducing the applied magnetic field, B, in order to compensate for the continual increase in B_N, at fixed f. As this magnetic field shift of ESR correlates with the polarization of the nuclei, EDESR can be used to set and measure the state of nuclear spins: the nuclear polarization can be set by performing ESR while down sweeping the magnetic field. The nuclear polarization can then be ascertained by identifying the magnetic field value at which ESR becomes possible on a subsequent up sweep of the magnetic field [6,7].

3. Timescales

Since long mean free path electrons mediate the dominant interaction between nuclear spins in the quantum Hall regime [5,12] it is expected that the relaxation times for the latter, as well as decoherence/dephasing effects, will occur on large enough time scales to allow relatively long-term information storage and controlled electron mediated nuclear spin transfer in such systems. Our program includes evaluating and measuring these time scales for specific systems, as well as understanding of how these times are modified by the use of clusters of polarized nuclear spins, rather than individual well-separated atoms bearing nuclear spin.

The dynamics of the nuclear spins is governed by their interactions with each other and with their environment. Various time scales are associated with this dynamics: there will be the relaxation time T_1, associated with energy exchange and thermalization of a spin. Quantum mechanical decoherence/dephasing will occur on the time scale T_2. Generally, there are many dynamical processes in the system, so T_1 and T_2 may not even be uniquely, unambiguously defined. For low temperatures we expect $T_1 > T_2$. The expectation has been that various processes of energy exchange will be frozen at zero temperature: $T_1 \to$ very large, but there still might be some dephasing (finite T_2) owing to quantum fluctuations. There are various extreme examples of theoretical prediction, ranging from no decoherence to finite decoherence at low temperatures [11], depending on the model assumptions.

In order to consider programming of a memory cell, we have to identify the Rabi time scale of single-spin rotations owing to their interactions with an external NMR magnetic field, T_{NMR} and the time scale T_{int} associated with evolution owing to the pairwise spin–spin interactions. A preferred relation for coherent quantum–mechanical dynamics is then $T_1, T_2 \gg T_{\mathrm{NMR}}, T_{\mathrm{int}}$. Furthermore, having $T_{\mathrm{int}}/T_{\mathrm{NMR}} \gg 1$ would simplify control of the nuclear spins. Of the time scales defined, T_2 is expected to be the most sensitive to the size of the nuclear spin cluster.

4. Nuclear spin memory cells and elementary nuclear spin logic functions

Information storage is envisioned to occur here within small nuclear-spin-active nanoscale dots fabricated using semiconductor lithography. The reading and writing of a given memory element is achieved through the application of electron spin resonance and nuclear magnetic resonance on a dot: the reading of a memory cell state is accomplished by measuring the Overhauser shift (B_{N}) in EDESR. A '1' state is written on a cell by exploiting the flip–flop interaction between conduction electrons and nuclear spins [6]. Here, electrons which are necessary for electron spin resonance can be introduced or removed from a cell by applying a potential to a 'gate'. And, this mechanism provides a convenient method for cell selection, for the microwave write operation. A cell that has been set to the '1' state tends to exhibit a slow post-write decay of polarization characterized by a relaxation time which depends on physical parameters, as in Fig. 1(g). A dot can be reset through NMR. Selectivity in erasure can be partly effected by using the sensitivity of the NMR resonance to the gate controlled electron density in the nuclear vicinity.

The coupling of isolated nuclear spin clusters by quantum Hall electrons dressed as spin excitons [11] leads to nuclear spin transfer between cells (see Fig. 1). And, this can be utilized to build up 2-bit logic devices that are based on a control-bit-dependent-modification of a target bit that then guides the response of the target bit to further manipulating operations. That is, a function that operates on two bits and leaves the second (target) bit unchanged if the first (control) qubit is '0', and flips the second (target) bit if the first (control) bit is '1'.

See Fig. 1. For example, when one cell is in the '1' state and the other is in the '0' state, the polarization in the '0' cell tends to grow with time at small times, followed by decay at larger times, and the polarization of the '1' cell tends to decay faster than in the decoupled-cell case (Fig. 1(c) and (d) or Fig. 1(e) and (f)) when there is coupling between the spin dots. Associated with this is a non-vanishing Overhauser shift in the cell that was initialized to '0' and a faster decay of the Overhauser shift in the cell that was initialized to '1'. It turns out that this can be used to select the response of the target cell to a sequence of microwave and RF operations that will have an influence on the target cell only when the target cell has been appropriately conditioned by the control cell. And, this can help realize a logic function where one operates on two cells at a time and leaves the second bit unchanged if the first is in the '0' state, and flips the second bit if the first is in the '1' state.

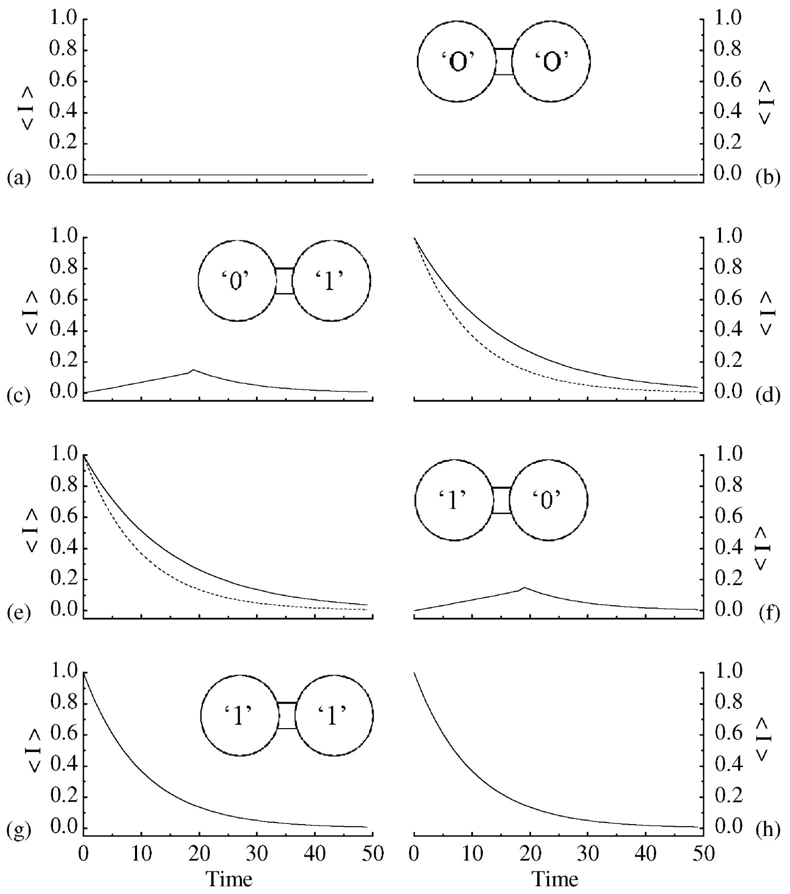

Fig. 1. The time dependence of the nuclear polarization in a pair of dots. The dot polarization’s are ‘initialized’ to states ‘0’ and ‘1’ as shown. The figure illustrates the effect of dot interaction in the quantum Hall regime. Panels [(c) and (d)] show that polarization transfer via conduction electrons leads to a gradual polarization increase for small times in the left dot, that was initialized to ‘0’, followed by polarization decay at larger times. (e) and (f) consider the complementary case. In (d) and (e), the dashed line indicates faster polarization decay due to dot–dot interaction in the dot with the ‘1’ state.

5. Summary

The ability to control and measure the spin state of a nuclear domain is of interest because nuclei, which constitute the smallest unit of matter in solid state systems, can be utilized for nonvolatile information storage at extremely high storage densities. The realization of *electrically controlled* electron mediated nuclear spin–spin interaction is useful because this capability would lead to the development of electrically switchable nuclear spin based logic functions in semiconductors. As the quantum Hall regime with the associated vanishing longitudinal resistance improves the sensitivity of electrical resonance detection techniques that are useful for spin state readout, and also increases relaxation/coherence times, we have suggested an approach for realizing nuclear spin memory and logic devices in quantum Hall systems.

Acknowledgements

We acknowledge discussions J.H. Smet and K. von Klitzing of the Max-Planck-Institute FkF, Stuttgart.

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