Photonic and microwave manipulation of nuclear spin qubits

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Recent advances of semiconductor device miniaturization strongly necessitate to take into account the influence of the quantum mechanical effects on the device performance since the statistical behavior of quantum system may result in unpredictable device parameter fluctuations. These concerns may ultimately force the industry to consider alternative schemes for electronics and to embrace nonclassical electronic behavior. For example, the possibilities of controlling the electron and nuclear spin instead of its charge give rise to the so-called spintronics [1]. The coherence of the quantum states plays a key role in the quantum states temporal evolution. Coherent approaches to electronics offer two major advantages [1].

1. Interference between two coherently occupied quantum states separated by the energy E can result in rapid oscillations of charge displacement or spin orientation magnetization) with a frequency E/h driving the operation of ultrafast devices and permitting to tune the device operating frequency. Magnetic field can control electron spin precession frequencies in semiconductors at a rate of tens of gigahertz per tesla.

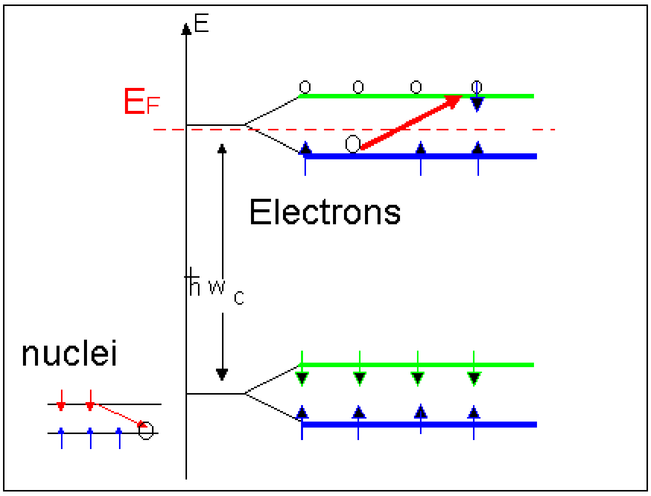
2. Interference may be used in quantum computation where the computational quantum bits (qubits) are the nuclear or electron spins that are well isolated from their environment and whose mutual interactions are well controlled.

The electron spin qubits have an essential disadvantage from the point of view of the quantum computation applications. The polarization of electron spins cannot be stored for a long time since it rapidly vanishes after the controlling signal is switched off. The nuclear spin qubits, on the contrary, possess sufficiently long relaxation times T1, up to several hours at low temperatures [2]. Hence, nuclear spins can be considered as the best suitable candidates for a qubit [3].

Moreover, even in the absence of the external magnetic field, the hypefine can produce Zeeman splitting of the conduction electron spins, equivalent to that of an external field of several tesla. This is an example of a "potential" magnetic field caused by the nuclear spin polarization.

We will present here our recent theoretical results on relaxation and decoherence processes of nuclear spin qubits in low-dimensional semiconductors and nanostructures [3]-[6] and on possibility of optical and microwave manipulation of nuclear spins in these systems. The free electron spin system can be optically excited by an elliptically polarized light wave [2].

The spatially inhomogeneous distribution of free electrons, or a dynamic grating, can be created, for example, by two interfering laser beams. The creation of different kinds of dynamic laser gratings is a well known [7] process. Consequently, the optically induced magnetization of the free electron system would also be spatially inhomogeneous. Optical spin excitation [2]and polarized electron spin transport in semiconductors are strongly coupled to the nuclear spin subsystem [8]. The magnetization can be transferred from electrons to nuclei due to hyperfine interaction mechanism. The electron spin polarization then would rapidly vanish after the removal of the external radiation while the spatially inhomogeneous induced spin polarization of the nuclei remains stored for a sufficiently long relaxation time T1. This process may be used for writing and storage of the information. The reading of the stored information can be realized through the creation of the free electron dynamic grating, this time with a non-polarized light. The dynamic electron grating would receive the spatially inhomogeneous magnetic moment from the polarized nuclei very rapidly through the reverse process of the hyperfine interaction.



The hyperfine interactions are believed to play a central role in solid state electronics based realizations of the future quantum computation devices [3,4]. The main ingredients are nuclear spins, qubits, coupled by the hyperfine interaction to a phase coherent electron spin system, Fig.1,such as the non-dissipative conduction electron state in quantum Hall systems.

The quantum Hall systems are realized in a two-dimensional electron gas (2DEG) existing in a doped heterojunction [9]. The electromagnetic and optical properties of the low-dimensional electron gas in heterosructures are essentially different from the ones in the bulk. The 2DEG mobility is extremely high at low temperatures.

The energy spectrum of 2DEG subjected to the external magnetic field *B* consists of a number of discrete Landau levels with an allowed number of states per unit area $n(B)=eB/h$ for each level [9] where h is the Planck constant. Typically, the Landau levels contain both spin states at low magnetic fields, and split into two (Zeeman splitting) as the magnetic field is raised. In the quantum magnetic limit case, for a sufficiently large magnetic field B, all electrons lie in the lowest Landau level.

At temperatures of an order of 1K and in magnetic fields of several Teslas, there are intervals of the magnetic field for which the electrons fill up an integer number *nu* =1,2,... of the Landau levels. The electron gas then forms a non-dissipative quantum Hall effect (QHE) fluid. The Hall resistance exhibits a plateau while the dissipation of the conduction electron gas (the magnetoresistance) approaches zero.

Nuclear spin polarization is detectable by measuring peculiarities of the electron transport in a semiconductor device under a microwave radiation as is in the case of the most recent measurements of this kind. Optical excitation of the charge carriers modifies the polarization of the underlying nuclear spin subsystem, thus creating spatially inhomogeneous hyperfine magnetic fields in a sample. Undesirable light absorption and transitions can be avoided by using non-resonant light frequencies. The influence of the spin-orbit coupling on the top valence band position in many cases can be neglected, but in GaAs the displacement equals 0.34eV and should be retained [9,10]. The propagation of the light wave in a heterostucture is described by a slab waveguide model [11]. A single-mode regime for TE modes can be achieved even for a very thin layer since the TE0 do not nave any cutoff [11].

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