A new mechanism for the nuclear spin depolarization in a spin diode

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A new mechanism for nuclear spin diffusion via virtual spin excitons under the conditions of integer quantum Hall effect is proposed. This mechanism significantly enhances the range of nuclear spin interaction along the magnetic length, and therefore may explain the nuclear spin depolarization in a spin diode.

Recently Kane, Pfeiffer, and West[1] reported the observation of a remarkable current-voltage characteristic of a novel device, which they named "spin diode." In this device the current passes across a junction between two coplanar 2DEG's, in which $\nu > 1$ on one side and $\nu < 1$ on the other, and the Fermi energy E_F crosses between different spin levels at the junction. The 2DEG is highly conducting, except for the depletion layer (with the width L_{ex} on the order of several hundred angstroms), where $\nu = 1$. Depending on the strength of magnetic field, the ratio L_{ex}/l_B can be on the order of or larger than unity. Here $l_B = (\hbar c/eB)^{1/2}$ is the magnetic length. Since E_F is in close proximity to different spin levels on the opposite sides of the junction, any passage of an electron across the junction is followed by a spin flip, which can take place due to the hyperfine interaction between the electron spins and the nuclear spins in the depletion layer. Thus the stream of electrons across the junction leads to nuclear spin polarization in the depletion layer. If the rate of nuclear spin relaxation within the depletion layer is sufficiently low, we may reach a case in which the spin polarization inside the junction is saturated, and so the electrical current across the junction will diminish.

This current is therefore strongly dependent on the rate of nuclear spin depolarization within the depletion layer. It should be noted that under operation conditions of the diode (i.e., $H \propto 15$ T, $T \geqslant 100$ mk) the nuclear spin polarization by the external magnetic field is negligible, so that the entire region outside the depletion layer is depolarized and can be regarded as a spin reservoir.

The nuclear spin relaxation directly to the electronic spin system via the hyperfine interaction was studied in Ref. 2. This mechanism is extremely slow at low temperatures, because the magnetic energy gap in the electron spectrum is large compared to

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the nuclear gap. Experimental feasibility of nuclear spin relaxation via electron spins was demonstrated in elegant experiments by the von Klitzing group.[3,4]

In this letter we propose a new mechanism of indirect spin transport from the polarized nuclei inside the junction to the nuclei outside it via the exchange of virtual electron-hole pairs (spin excitons[5,6]). This mechanism is associated with the hyperfine interaction. In contrast to the mechanisms proposed in Refs. 2 and 7, the magnetic energy gap is encompassed here by the virtual spin excitons. This circumstance accounts for a much more efficient process of nuclear spin flip at sufficiently low temperatures. The virtual character of the spin excitons, which transfer the nuclear spin polarization, removes the problem of the energy conservation in a single flip-flip process.

We consider a region of the heterostructure, in which the nuclear spins are temporarily excited (e.g., the depletion layer in the spin diode of Ref. 1), and we calculate the rate of spin diffusion from this region via the exchange of virtual spin excitons.

The Hamiltonian of the hyperfine interaction between a nuclear spin at a given position $\mathbf{R}$ and the electron spins can be written in terms of spin exciton operators[7] $\hat{A}_{\mathbf{k}}$ as follows:

$$\hat{H}_{e-n}(\mathbf{R}) \propto \sum_{\mathbf{k}} W(k^2)(\hat{A}_{\mathbf{k}}^{+}\hat{I}^{+}+\hat{A}_{\mathbf{k}}\hat{I}^{-})\exp[i(k_xX-k_yY)], \tag{1}$$

where $\hat{I}^{\pm}$ are the transverse components of the nuclear spin operator, and $W(\tilde{k}) = e^{-\tilde{k}^2/4}$, with $\tilde{k}\equiv kl_B$. This form of $W(\tilde{k})$ corresponds to the electrons in the Landau ground level.

The rate of the spin diffusion from a given nuclear site $\mathbf{R}_a$ in the polarized region is proportional to the probability for the transition $P(\mathbf{R}_a)$ of the polarization of the nuclear spin $\Downarrow$, located at $\mathbf{R}_a$, to the nuclear spin $\Uparrow$, located at $\mathbf{R}_b$, outside the polarized region, via the exchange of virtual spin excitons.

Using second-order perturbation theory with respect to $\mathbf{H}_{e-n}$, the desired rate of transition probability can be written in the form

$$\frac{d}{dt}P(\mathbf{R}_a) \propto \Big| \sum_{\mathbf{R}_b} \langle \Downarrow,\Uparrow | \hat{T}(\mathbf{R}_a,\mathbf{R}_b) | \Uparrow,\Downarrow \rangle \Big|^2 \delta(\epsilon_{\downarrow}^{a}+\epsilon_{\uparrow}^{b}-\epsilon_{\uparrow}^{a}-\epsilon_{\downarrow}^{b}), \tag{2}$$

where

$$\hat{T}(\mathbf{R}_a,\mathbf{R}_b) \equiv -(\hat{I}_a^{+}\hat{I}_b^{-}+\hat{I}_a^{-}\hat{I}_b^{+}) \int_0^{\infty} \frac{J_0(kR_{ab})}{E_{\mathrm{ex}}^{\mathrm{sp}}(k)} e^{-\tilde{k}^2/2} k d\tilde{k} \tag{3}$$

$$R_{ab} \equiv |\mathbf{R}_a-\mathbf{R}_b|,$$

and

$$E_{\mathrm{ex}}^{\mathrm{sp}}(\tilde{k}) \equiv |g|\mu_B B+\frac{e^2}{kl_B}\sqrt{\frac{\pi}{2}}\left[1-e^{-\tilde{k}^2/4}I_0\left(\frac{\tilde{k}^2}{4}\right)\right] \tag{4}$$

is the spin-exciton energy dispersion. In these expressions g is the effective electronic g-factor, μ_b is the Bohr magnetron, and k is the dielectric constant in the 2DEG region.

Ideally, the conservation of energy between the initial and the final states imposed by the delta function in Eq. (2) is strictly satisfied. In reality, however, because of the difference in local magnetic fields at the various nuclear positions, the initial- and final-state energies $(\epsilon_\uparrow^b, \epsilon_\downarrow^b)$ of the nuclei located outside the excited region fluctuate with respect to the corresponding energies $(\epsilon_\downarrow^a, \epsilon_\uparrow^a)$of the relaxing nuclei in this region.

The transition operator $\hat{T}(\mathbf{R}_a, \mathbf{R}_b)$ corresponds to an effective nuclear spin-spin interaction, which is analogous to the well-known Ruderman-Kittel-Yosida interaction in metals which exhibit the Friedel oscillations. In our case the interaction between the nuclear spins, given by the integral in Eq. (3), is a monotonic function of the distance between two nuclei which interact via the spin excitons. The negative sign in Eq. (3) indicates an attraction between the nuclear spins which may result in a ferromagnetic nuclear state.

Asymptotically, at large distances between interacting nuclei, $R_{ab} \gg l_B$, the important values of $\tilde{k}$ are on the order of l_B/R_{ab}, and are therefore much smaller than unity, so that both $e^{-\tilde{k}^2/2}$ and $E_{ex}^{sp}(\tilde{k})$ can be expanded to the lowest significant order in $\tilde{k}$ (i.e., to zero and to second order, respectively). Using the parabolic approximation for the spin-exciton dispersion

$$E_{ex}^{sp} \simeq \epsilon_{sp} \simeq +\tfrac{1}{4}\epsilon_c \tilde{k}^2, \tag{5}$$

where $\epsilon_c = (e^2/kl_B)(\pi/2)^{1/2}$ is the characteristic Coulomb energy, and the asymptotic behavior of the effective interaction, we can write Eq. (3) as

$$T(\mathbf{R}_a, \mathbf{R}_b) \propto -\sqrt{\frac{d}{R_{ab}}}\, e^{-R_{ab}/d}, \tag{6}$$

where

$$d \equiv \frac{l_B}{2}\sqrt{\frac{\epsilon_c}{\epsilon_{sp}}}. \tag{7}$$

This is the well-known behavior characterizing the interaction potential, which is mediated by the exchange of quasiparticles with a dispersion relation such as in Eq. (5). The range ΔR of this potential is determined by the critical wave number $k_0 = (2/l_B)(\epsilon_{sp}/\epsilon_c)^{1/2}$, as follows from the uncertainty principle: $\Delta R \cdot k_0 \simeq 1$. The spin-diffusion process is therefore governed by two characteristic length scales: the width, L_{ex}, of the polarized region and the range, d, of the effective interaction.

Using Eq. (5) for $E_{ex}^{sp}(\tilde{k})$, integrating over $\tilde{k}$, and finally using the asymptotic form of the modified Bessel functions after, integration over the unpolarized part of the sample, we obtain a rather simple expression for the nuclear spin diffusion rate

$$\frac{1}{\tau_{sd}} \propto \left(\frac{\hat{n} l_B^2}{\epsilon_{sp}}\right)^2 e^{-L_{ex}/d} \cos h^2 \left[\frac{(R - \frac{1}{2}L_{ex}}{d}\right], \tag{8}$$

where $\mathbf{R} \equiv \mathbf{R}_2 - \mathbf{R}_a$. Here R_2 and R_a are the positions of the nuclei in the unpolarized region and in the strip L_{ex}, respectively.

In summary, we have considered the depolarization of nuclear spins in a spin diode.[1] The proposed mechanism for nuclear spin diffusion via virtual spin excitons makes it possible to transfer nuclear spins over a distance longer than the magnetic length l_b. The long range nature of this mechanism is of considerable importance when the size of the region of excited nuclear spins, L_{ex}, is larger than the magnetic length l_B, which has been the case in recent experiments.[1]

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