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LETTER TO THE EDITOR

Realization of an effective ultrahigh magnetic field on a nanoscale

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Abstract
In tunnel junctions of which at least one side is a ferromagnet, very large magnetic polarization change ($\approx 0.1\mu_B$) and splitting of the spin-up and spin-down Fermi energy (≈ 0.1 eV) can be created under steady state finite current conditions (bias voltage ≈ 1 volt). This is much higher than can be created by the highest magnetic field on earth. We illustrate this with a specific calculation of a recently observed very large Hall effect in the Al side of a Co-I-Al tunnel junction. Other recent experiments that support this idea are discussed.

1. Introduction and summary

There is much recent interest in spin polarized transport in ferromagnetic tunnel junctions, motivated by the observed high DC magnetoresistance [1, 2], and their potential applications as magnetic sensors and nonvolatile memories. These structures are junctions of two metals with a thin (≈ 10 Å) layer of an insulator in between. They are symbolically denoted as an F-I-F structure where I stands for insulator. The spin polarized transport in this system has been studied theoretically without taking into account the electron–electron (e–e) interation [3–6][3] and including the e–e interaction [7–9]. It is found that in tunnel junctions [7], at least one side of which is a ferromagnet, under steady state moderate currents ($\approx 10^{-5}$ A) there will be a very large change in the polarization ($\approx 0.1\mu_B$) and splitting of the spin-up and spin-down Fermi energies (≈ 0.1 eV).

The implication of this splitting has not been explored. By applying different voltages, the Fermi levels can be moved and different parts of the band structure can be probed. Different physical characteristics of different parts of the band structure can be manifested. One can envision inducing different phase transitions by tuning the applied voltage.

Experimental results that illustrate the new physics that can happen as a result of the splitting are beginning to appear [9,10,17,18]. The big splitting of the spin-up and spin-down Fermi energies provides for an explanation of the bias dependence that is experimentally observed [9]. Here we discuss an illustration of the probing of a different part of the band structure with a detailed calculation of a giant anomolous Hall resistivity recently discovered

[3] Reference [6] did not take into account the spin accumulation effect, which is manifested mathematically as the continuity of the current as it goes from inside the metal across the junction.

in Co-I-Al tunnel junctions [10]. Good agreement with the experimental results are obtained. We then conclude by discussing two other experiments that provide further illustration for the conclusion discussed here.

The changes in the Fermi levels can in principle also be produced by external magnetic fields of strength of the order of 1000 Teslas. This field strength is much higher than can be created by the highest magnetic field on earth. This presents a possibility of a new area of research of ultrahigh magnetic field physics.

That a current can induce a magnetization in a ferromagnetic–paramagnetic junction (no insulator in between) was first discussed by Johnson and Silsbee [3] and van Son *et al* [4]. The magnetized current from the ferromagnet induces a magnetization in the paramagnet due to a spin-bottleneck effect and causes a splitting of the spin-up and the spin-down Fermi energies $\Delta\mu$. The ratio of this splitting to the driving current I is of the order of the resistance of the metal. This same reasoning can also be applied to the F-I-P structure with an insulator in between, and the magnetization and the splitting is of the same order of magnitude. The resulting magnetization from this 'spin accumulation effect' is very small and is different from the physics discussed here. For the F-I-P structure and our mechanism, the ratio $\Delta\mu/I$ is of the order of the resistance of the insulating barrier. This is several orders of magnitude larger than that expected from the spin accumulation effect.

2. Underlying framework

We first recapitulate briefly the reasoning that led to the splitting of the Fermi levels. The physics can be approximately described by the following sets of equations. The first is that of a global charge current conservation[4]:

$$\nabla \cdot J = -\partial\rho/\partial t. \tag{1}$$

Here J, ρ are the total (including both spins) current and charge densities. The second equation is the diffusion equation which expresses the current density for spin s, J_s, as a sum of (a) the external driving current $J_{0s} = \sigma_s E$ that is controlled by the conductivity σ_s and the external electric field E; (b) the current driven by a density gradient (diffusion) expressed as a gradient of the chemical potential $\nabla\mu_s = \nabla\rho_s/N_s$ through the density of states at the Fermi surface N_s and (c) the current driven by the internal electric 'screening' field ∇W_0[5]:

$$J_s = \sigma_s[\nabla\mu_s - \nabla W_0 + eE]/e. \tag{2}$$

Here σ_s is the conductivity for spin channel s. $W_0(r)$ is the local electric (screening) potential due to the other electric charges that is determined self-consistently: $W_0(r) = \int \mathrm{d}^3r' U(r - r')\rho(r')$ where U is the Coulomb potential. Because of this self-consistent screening, charge fluctuation dies off with a length scale λ called the screening length[6], which is of the order of 0.5 Å for metals. Finally, the magnetization density changes M relaxes with a length scale of $\bar{l}_{sf}$ where the bar indicates a renormalization effect due to the electric field [7]:

$$\nabla^2 M - M/\bar{l}_{sf}^2 = 0. \tag{3}$$

For the systems of interest, the spin diffusion length $\bar{l}_{sf}$, is of the order of 1000–10000 Å and is much larger than the screening length λ. Because of these two very different length scales,

[4] This corresponds to equation (4) of [3].
[5] This corresponds to equation (1) of [3].
[6] The screening length is $\lambda = \sqrt{1/4\pi\chi_0 e^2}$ where the effective density of state $\chi_0 = 0.5(\sum_s \sigma_s)/[0.5\sum_s \sigma_s/N_s]$.

there is a delicate balance in the current from the charge and the magnetization diffusion that has to be maintained.

One can solve these sets of equations on each side of the junction. The currents on opposite sides of the junction are related by the boundary condition that the current J_s is continuous across the junction and that

$$\Delta\mu_s - \Delta W = r(1 - s\gamma)J_s \tag{4}$$

where $r(1 - s\gamma)$ is the resistivity of the junction for spin $s = \pm 1$.

The final solution can be developed in increasing powers of $\lambda/\bar{l}_{sf}$. Solving equations (1)–(3) for a junction of thickness d at the origin, we find 'dipole layers' of charge (ρ) and magnetization (M) densities that peaks at the junction and dies off exponentially away from the junction with a functional form $f(z, l) = \exp[-(|z| - d/2)/l]$[7]:

$$\rho \approx \rho_1 f(z, \lambda)\lambda/\bar{l}_{sf} + \rho_2 f(z, \bar{l}_{sf})\lambda^2/\bar{l}_{sf}^2, M \approx M_0 f(z, \bar{l}_{sf}). \tag{5}$$

In this letter, we use units of M in terms of the Bohr magneton. The charge and magnetization densities are now coupled: $\rho_{10} = G\rho_{20}$ where G is a coefficient of the order of unity[8] $\rho_{20} = M_0 D_M/D_D$. Here D_M (D_D) is the diffusion constant for the magnetization (charge) that can be expressed in terms of the conductivities[9]. The charge dipole layer densities are smaller than the magnetization densities by a factor $\lambda/\bar{l}_{sf}$! This comes from the two very different length scales of change for the charge and the magnetization degrees of freedom. There is a small correction to the charge density that is of a much longer range than the screening length. In general the constants ρ_i, M_0 on opposite sides of the junction can be different from each other. The total charge on opposite sides of the junction are opposite in sign and equal in magnitude, of course.

After matching the boundary condition (equation (4)) one obtains for the magnetization and the Fermi energy splitting[10]:

$$M_0 = FrJ \tag{6}$$

$$\mu_+ - \mu_- = 0.5M(1/N_+ + 1/N_-) \tag{7}$$

where F is a coefficient of the order of the inverse density of states at the Fermi energy[11]. It is different for parallel and antiparallel alignment of the magnetizations on opposite sides of the junction. Thus the magnetization density induced is controlled by the resistance of the junction, not of the metal! To illustrate the application of this, we first calculate the Hall conductivity σ_{xy} of Al in a Co-I-Al junction.

3. Anomolous giant Hall resistivity

Otani *et al* [10] recently measured the Hall coefficient of Al in a Co-I-Al structure. They found that above a threshold voltage of about 1 volt, there is a rapid increase in the Hall voltage that is of the same sign (negative) but much larger than the ordinary Hall coefficient of Al. This effect disappears as the temperature is increased from 30 to 150 K. Their original explanation

[7] From Gauss's law, the self consistent internal electric field is $\nabla W_0 \approx 4\pi\lambda(\rho_1 f(z, \lambda) + \rho_2 f(z, \bar{l}_{sf})\lambda/\bar{l}_{sf})$.

[8] $G = -(\sigma^2/(\chi_0^2 D_M) - b\sigma/\chi_0)\rho_{20}/[(D_M - b\sigma)]$. $b = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$. $\sigma = 0.5\sum_s \sigma_s$.

[9] $D_M = 0.5\sum_s s\sigma_s/(eN_s)$. $D_D = 0.5\sum_s \sigma_s/e\chi_0$.

[10] For the systems that we look at, the ΔW term is much smaller and neglected.

[11] $F = [(b - \gamma)/\bar{N}_D - (1 - \gamma b)/\bar{N}_S]4/[1/N_{SA}N_{DS} - 1/N_{DA}N_{SS}]$; $1/N_{S(D)} = 1/N_+ \pm 1/N_-$, $f_{S(A)} = f^> \pm f^<$ for any function f. The superscript $<, >$ indicates the left and the right side of the insulator. b is a measure of the asymmetry of the conductivity between the spin-up and the spin-down band. Note that because the spin-up and spin-down Fermi energies are different, the densities of states at the Fermi energies of the spin-up and spin-down electrons in Al will be different.

in terms of an extraordinary Hall effect is inapplicable with a revised estimate[12] of the Hall resistivity that is several orders of magnitude higher.

In our picture, as the external voltage V is increased, the spin-up and spin-down Fermi energies will move apart by an amount 2Δ proportional to V. The sample is polycrystalline experimentally [10]. Without detailed knowledge of the nature of this polycrystalline sample, for simplicity we consider the crystal structure as a single fcc crystal of bulk Al with lattice parameter 4.0491 Å and have taken the direction of the magnetization parallel to the z symmetry axis of Al. We have calculated the Hall conductivity σ_{xy} from first principles as a function of Δ.

Our calculations are performed using the band structure obtained with the self-consistent full-potential linearized augmented-plane-wave (FLAPW) method [11] under the generalized gradient approximation (GGA) [12] with spin–orbit coupling [13, 14][13]. The conductivity is calculated using the Kubo formula. The Brillouin zone sampling is performed using 4000 special k-point meshes, which yielded 315 points in the irreducible Brillouin zone[14]. The dependence of conductivity on the frequency have been tested on the Kerr effect of bcc Fe. For an inverse lifetime $\Gamma = 0.45 \sim 0.65$ eV, our result is in very good agreement with the experimental results. The Hall conductivity is the zero frequency limit of the conductivity.

Our result for the Hall conductivity is shown in figure 1. The sign and the shape (including the threshold) are in good agreement with experiment. The physics of the threshold and the temperature dependence can be understood as follows: the band structure of Al with the spin-up and spin-down Fermi levels is shown in figure 2 for the case $\Delta = 0.2eV$. Two bands cross along the direction XZW. The crossing is a spin–orbit split. At zero magnetization, this crossing is below the Fermi energy. When the spin-up and the spin-down Fermi levels move apart, one of them will move towards this crossing and a significant interband contribution will come in for the Hall conductivity. The threshold is determined by the distance between the energy at this crossing and the Fermi energy at zero field. Because the spin–orbit band gap is very small, we expect the interband contribution will decrease significantly when the temperature becomes comparable to this band gap.

The magnitude of our result depends on the scattering time $\tau = \hbar/\Gamma$. Our results for σ_{xy} is in the range of 1–10 $1/\Omega-$cm. Because of the nonuniformity of the current flow due to the geometry of the experimental sample, and because we do not know the detailed material characteristics of the polycrystalline experimental sample, we do not expect to get exact quantitative agreement with the experimental results. If we pick a typical $\Gamma = 0.25$ eV, our result is in good agreement with the experimentally revised value of $\rho_{xy} = 1.5 \times 10^{-8}\Omega-$m for an average $\rho_{xx} = 3.4 \times 10^{-6}\Omega$ m. (Recall that $\sigma_{xy} = \rho_{xy}/\rho_{xx}^2$.) This diagonal resistivity is consistent with recent unpublished results by the same authors for an ohmic (F–P) Co–Al junction.

[12] From figure 3 of [6], we get a Hall resistance of about 0.3 Ohm for a current of 10^{-5} A. To get the resistivity, we have to multiply by an area A and divide by a length l. For A, we took 300 nm $\times 0.5\,\mu$m. The first factor is the thickness that was quoted. The second we estimate from the picture. For l, we took the length of the Hall bar which we estimate to be 3 micron. From these, we get a Hall resistivity $\rho_{xy} \approx 1.5 \times 10^{-8}$ Ohm-m. This is much less than the 1.8×10^{-17} Ohm-m in the paper.

[13] Spin-orbit interactions can be considered via a second variational step using the scalar-relativistic eigenfunctions as basis.

[14] For a detailed discussion see [15]. Here, we first calculate the imaginary part from the momentum sum, the real part of conductivity $\sigma_{xy}(\omega)$ is obtained by performing a Kramers–Kronig transformation as

$$\sigma_{xy}^{(1)}(\omega) = \frac{2}{\pi} P \int_0^\infty \frac{x}{x^2 - \omega^2} \sigma_{xy}^{(2)}(x) \mathrm{d}x \tag{8}$$

where, $\sigma_{xy}^{(2)}$ is the imaginary part of the $\sigma_{xy}(\omega)$. The integral are performed up to 2.0 Ry, and about 10000 ω mesh is used. The static conductivity shown in figure 1 corresponds to $\omega = 0$.

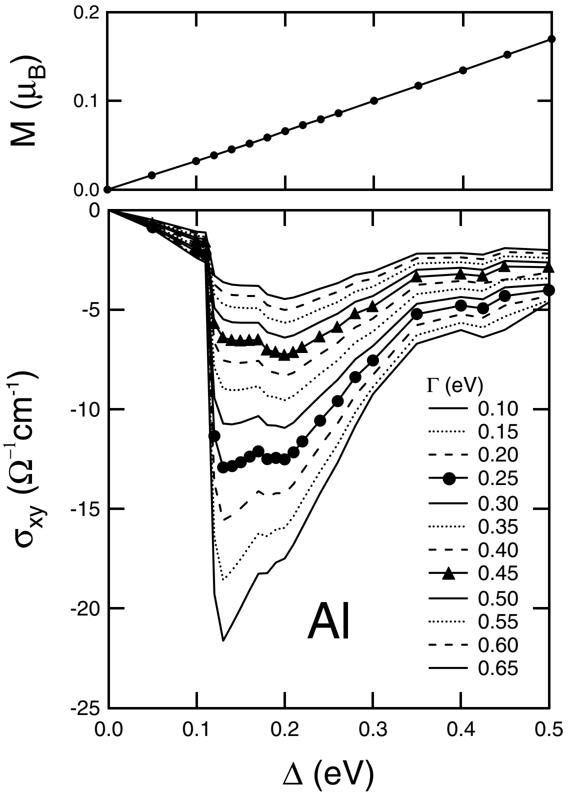

Figure 1. Energy bands for fcc Al in the ferromagnetic ground state with Fermi level splitting $2\Delta = 0.4$ eV. The Fermi levels are shown by the solid horizontal lines.

Our picture can be tested further experimentally. In our calculation, the Hall resistance goes through a maximum and decreases as the bias voltage is further increased. So far the experiment was carried out up to a bias when the maximum of ρ_{xy} was reached. We predict that the Hall resistivity will decrease as the voltage is further increased. Next, we discuss some other recent experimental results that support the present picture.

Moodera and coworkers [17] recently found a fascinating series of bias dependences, including a negative junction magnetoresistance, for a F-I-P-F structure with varying thickness for the paramagnet [16]. To explain their result, they assumed a model with different spin-up and spin-down Fermi energies. The result discussed here provides for a possible justification of the model that they have used.

Ono *et al* [17] recently studied the magnetoresistance of ferromagnetic single-electron transistors made from tunnel structures. Depending on the gate voltage, this device can be in an on- or an off-state. In the on-state, they found a magnetoresistance ratio of about 4 %. They observed a ten-fold increase of the magnetoresistance ratio in the off-state. In the off-state, the transport depends exponentially on the activation barrier which is a sum of the Coulomb charging energy and the difference of the Fermi energy on the left and the right hand side of the junction [18]. The large magnetoresistance can be understood in the present picture from the different splitting of the Fermi levels between the cases of the parallel and the antiparallel alignment of the magnetizations.

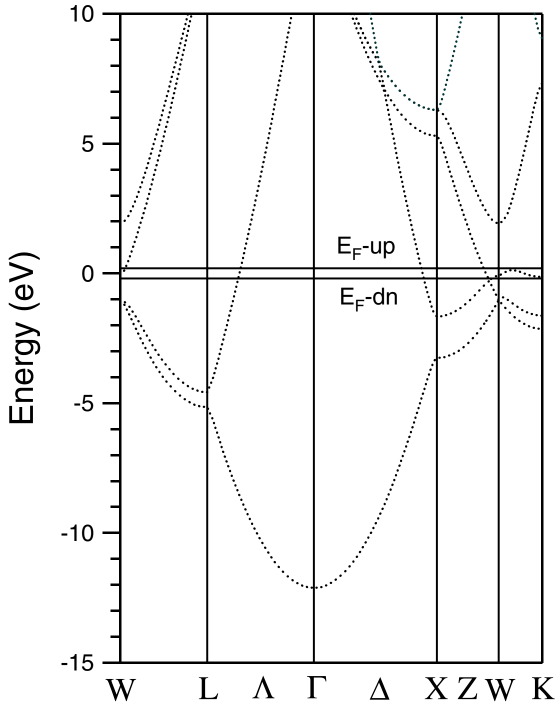

Figure 2. Dependence of conductivity and the spin polarization on the spin-up spin-down Fermi level splitting $2\Delta = E_F^{up} - E_F^{dn}$.

In conclusion, we propose that magnetic tunnel junction provides for new opportunities to observe high magnetic field physics. Theoretical and experimental evidences are provided to support this claim.

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