Spin injection in metals and polarization of nuclei

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Spin injection arises when current is made to flow through a contact between a ferromagnet and a metal. Spin injection amplifies strongly the ESR signal in a metal and produces an appreciable polarization of the nuclei over the electron spin diffusion length, which can reach several centimeters.

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Clark and Feher,[1] by investigating the polarization of nuclei in InSb in which the electron gas was heated, were the first to observe in semiconductors the spin injection connected with the difference between the g-factors of the electrons in the junction and in the semiconductor. Spin injection produced when current is made to flow in a contact between a ferromagnet and a semiconductor was investigated theoretically in[2].

In this article we wish to call attention to the possibility of realizing spin injection in a normal metal and to show that, notwithstanding the small degree of average polarization of the electrons, the spin injection can lead to significant effects in ESR in metals and nuclear polarization.

The electrons contributing to the conductivity of metals are those in the Fermi surface in a layer of the order of kT. Therefore, when current is made to flow through a contact between a ferromagnet and a metal, noticeable polarization of the electrons will take place in a narrow layer near the Fermi surface, and this leads to a difference $\Delta\zeta$ between the chemical potentials of electrons with opposite spins. To find this difference, we use the diffusion equation for the spin part of the distribution function $\sigma(\epsilon)=n_+(\epsilon)-n_-(\epsilon)$

$$D(\epsilon)\frac{\partial^2\sigma(\epsilon)}{\partial x^2}-\frac{\sigma(\epsilon)}{\tau_s}=0\ . \tag{1}$$

Here $D(\epsilon)$ is the diffusion coefficient of electrons with energy ϵ, τ_s is their spin relaxation time, and x is the coordinate normal to the surface of the contact.

We have neglected in (1) the drift term, which is small in terms of the parameter $eEL_s/\zeta \ll 1$, where $L_s=\sqrt{D\tau_s}\,|_{\epsilon=\zeta}$ is the spin diffusion length, ζ is the Fermi energy of the electrons in a nonferromagnetic metal, and E is the electric field intensity.

Equation (1) must be solved with the boundary condition

$$J_s(\epsilon)\,|_{x=0}=\frac{a}{e}\,J(\epsilon). \tag{2}$$

Here $J_s(\epsilon)=D(\epsilon)(\partial\sigma/\partial x)$ is the flux density of spins with energy ϵ, $J(\epsilon)=\frac{1}{3}eEl(\epsilon)v(\partial n_0/\partial\epsilon)$ is the current density produced by electrons of energy ϵ, α

is the degree of polarization of the current from the contact between the ferromagnet and the metal, $l(\epsilon)$ is the mean free path, and v is the particle velocity.

The solution of (1) with boundary condition (2) is of the form

$$\sigma(\epsilon) = -\alpha e E L_s(\epsilon)\frac{\partial n_0}{\partial \epsilon} e^{-\frac{x}{L_s(\epsilon)}} , \quad (3)$$

where $L_s^2(\epsilon) = D(\epsilon)\tau_s$. It is seen from (3) that the separation of the Fermi surfaces at distances small in comparison with the spin-diffusion length is $\Delta\zeta = \alpha eEL_s$. We note immediately that L_s can be very large and, for example in aluminum (see below) it can be of the order of 1 cm. The average electron polarization is $p = \langle\sigma\rangle/N \sim \alpha eEL_s/\zeta \ll 1$. However, if the sample is placed in an external magnetic field H parallel to the direction of the spin polarization, then in the presence of spin injection the magnetization of the electrons is

$$M = g\mu_0 \frac{\partial N}{\partial \zeta}(g\mu_0 H + \alpha eEL_s) \quad (4)$$

where μ_0 is the Bohr magneton. Since the ESR signal is proportional to the stationary magnetization, the change of the signal due to the injection is

$$\frac{I}{I_0} = 1 + \alpha\frac{eEL_s}{g\mu_0 H} . \quad (5)$$

If the nuclei have spin, then, owing to the scattering of the polarized electrons by the nuclei, the latter will become polarized. D'yakonov and Perel'[3] calculated the average projection of the nuclear spin $\langle I_z\rangle$ in a weak magnetic field. Recognizing that $\Delta\zeta = \alpha eL_s$ and using expression (12) of[3], we obtain

$$\langle I_z \rangle = \tfrac{2}{3} I(I+1)\frac{H^2}{H^2 + \delta H_L^2}\,\mathrm{th}\left(\alpha\frac{eEL_s}{kT}\right) . \quad (6)$$

Here I is the spin of the nucleus, H_L^2 is the mean squared local magnetic field produced at the nucleus by the surrounding nuclei, and $\delta = 2$—3.[4]

Let us estimate the order of magnitude of the observed effects. In aluminum, owing to the small spin-orbit coupling, we have $\tau_s/\tau_p \sim 10^5$.[5] This means that at $\tau_p \approx 10^{-10}$ sec, which is easily realized in pure aluminum, we have $\tau_s \sim 10^{-5}$ sec and $L_s \sim 1$ cm. In a field $E \sim 10^{-4}$ V/cm at $T = 1$ °K we then have $eEL_s/kT \sim 1$. Such fields correspond under these conditions to current density $\sim 10^4$ A/cm^2, and to only 1 W/cm^3 of power dissipation. For ESR the situation is even better. Under these conditions, at $g\mu_0 H \sim 10^{-2}$ °K (fields of this magnitude, $H \approx 10^2$ Oe, were used in ESR in lithium[6]), the ESR signal will be amplified by ten times if $\alpha \approx 0.1$.

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