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Spin coulomb Drag Effects In Absence Of Spin-Flip Process

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Abstract

Spin Coulomb Drag (SCD) is now a well known phenomenon in the field of spintronics. In this paper we have discussed the SCD in absence of spin-flip process. From our theoretical analysis we have shown that the spin-flip process either its presence or absence does not affect the phenomenon of SCD. Some suggestions to reduce the SCD effect, which is a cause for decay mechanism for spintronic devices are also discussed.

Keywords: Spintronics; Spin Coulomb Drag; Transresistivity; Spin Drag; Spin Diffusion; Spin Current; Spin-Flip.

Introduction

The field of spintronics is related with the spin degree of freedom of the electrons. It is aimed at proposing, designing and developing electronic devices to harness spin phenomena. Spintronics relies on the direction of an electron's rotation to convey data instead of electronic charges. Roughly speaking, an electron can be viewed as a tiny ball that spins like a baseball. The difference is that a baseball can spin at any speed, but an electron can only spin at a certain speed -- either counterclockwise or clockwise. Therefore, we can use one spin state to represent 'zero' and another to represent 'one.' Because a single electron can carry this information, this takes much less time and much less energy. One of the important theories in this field is Spin Coulomb Drag (SCD). It is well established [1, 2, 3] that the Coulomb interaction induces momentum transfer between the carrier population of "up" and "down" spins. This results in a Spin Coulomb Drag effect within a single two dimensional electron gas (2DEG) layer. This is analogous to the conventional Charge Coulomb Drag, which occurs between spatially separated layers.

Theory

SCD manifests itself [4] when a current carried by active spin-down electrons $\vec{J_{\bar{\sigma}}}$ transfer momentum through the Coulomb interaction to the passive spin-up electrons carrying no current ($\vec{J_\sigma} = 0$). This process induces a gradient of electro chemical potential, which results in a "spin electric field" $\overrightarrow{E_\sigma}$. The direct measure of SCD is the spin-drag transresistivity defined as:

$$\rho_{\sigma\bar{\sigma}} = \frac{E_\sigma}{J_{\bar{\sigma}}} \quad when \quad J_\sigma = 0 \qquad (1)$$

In our earlier paper [5] we have discussed SCD considering spin-flip possibility and it is found that the spin- flip process from electron-impurity collisions does not effectively contribute to momentum transfer between the two spin channels. But, the situation looks quite different for electron-electron collisions. The collision of an up-spin electron with a down-spin electron leads to a momentum transfer that is preferentially oriented against the relative velocity of the two electrons and is proportional to the latter [2].

Here we calculate the spin-drag transresistivity assuming weak electron-electron and electron-impurity collision and ignoring the spin-flip process altogether. If $\vec{v_\sigma}$ is the velocity of the centre of mass (m^*) of electron with spin σ and N_σ is the number of such electrons phenomenological equation of motion can be written as:

$$m^* N_\sigma \dot{\vec{v_\sigma}} = -eN_\sigma \overrightarrow{E_\sigma} + \overrightarrow{F_{\sigma\bar{\sigma}}} - \frac{m^*}{\tau_\sigma} N_\sigma v_\sigma \qquad (2)$$

Here, $\overrightarrow{E_\sigma}$ is the electric field corresponding to spin σ electrons. σ stands for up-spin where as $\bar{\sigma}$ for spin-down electrons. $\frac{1}{\tau_\sigma}$ is the scattering rate i.e. rate of change of momentum of electrons with spin σ due to electron-impurity scattering, in which electron does not flip its spin and is basically known as Drude scattering rate. $\vec{F}_{\sigma\bar{\sigma}}$ is the Coulomb force exerted by spin $\bar{\sigma}$ electrons by spin σ electrons. The net force exerted by spins of same orientation vanishes by virtue of Newton's third law. So,

$$\vec{F}_{\sigma\bar{\sigma}} = -\vec{F}_{\bar{\sigma}\sigma} \qquad (3)$$

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By Galilean invariance, this force can only depend on the relative velocity of the two components. Hence in the linear approximation, for weak Coulomb coupling [1] we can write

$$\overrightarrow{F_{\sigma\bar{\sigma}}} = -\gamma m^* N_\sigma \frac{n_{\bar{\sigma}}}{n}(v_\sigma - v_{\bar{\sigma}}) \quad (4)$$

Here n_σ is the density of electrons with spin σ and $n = n_\sigma + n_{\bar{\sigma}}$ is the total density of electrons, γ is the spin-drag co-efficient. Putting the value of $\overrightarrow{F_{\sigma\bar{\sigma}}}$ from equation (4) into equation (2) the equation of motion takes the form

$$m^* N_\sigma \dot{\overrightarrow{v_\sigma}} = -eN_\sigma \overrightarrow{E_\sigma} - \gamma m^* N_\sigma \frac{n_{\bar{\sigma}}}{n}(v_\sigma - v_{\bar{\sigma}}) - \frac{m^*}{\tau_\sigma} N_\sigma v_\sigma \quad (5)$$

Applying Fourier transformation $f(\omega) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} f(x)e^{-i\omega x}\,dx$ which is generally a complex valued function to equation (5) with respect to time, we have

$$-i\omega m^* N_\sigma v_\sigma(\omega) = -eN_\sigma \overrightarrow{E_\sigma}(\omega) - \gamma m^* N_\sigma \frac{n_{\bar{\sigma}}}{n} v_\sigma(\omega) + \gamma m^* N_\sigma \frac{n_{\bar{\sigma}}}{n} v_{\bar{\sigma}}(\omega) - \frac{m^*}{\tau_\sigma} N_\sigma v_\sigma(\omega) \quad (6)$$

Using the current density equation

$$\overrightarrow{J_\sigma}(\omega) = -en_\sigma \overrightarrow{v_\sigma}(\omega) \quad (7)$$

The above equation takes the form

$$E_\sigma(\omega) = \left(\frac{-i\omega m^*}{n_\sigma e^2} + \frac{m^*}{n_\sigma e^2 \tau_\sigma} + \gamma \frac{m^* n_{\bar{\sigma}}}{n n_\sigma e^2}\right)\overrightarrow{J_\sigma}(\omega) - \left(\gamma \frac{m^*}{ne^2}\right)\overrightarrow{J_{\bar{\sigma}}}(\omega) \quad (8)$$

This is the expression for electric field.

The spin resistivity matrix $\rho_{\sigma\bar{\sigma}}$ is defined as the co-efficient of proportionally between the electric field and the current:

$$\overrightarrow{E_\sigma} = \sum_{\bar{\sigma}} \rho_{\sigma\bar{\sigma}} j_{\bar{\sigma}} \quad (9)$$

Comparing this definition with equation (8) the complete form for the resistivity matrix can be written as

$$\rho_{\sigma\bar{\sigma}} = \begin{bmatrix} \frac{-i\omega m^*}{n_\sigma e^2} + \frac{m^*}{n_\sigma e^2 \tau_\sigma} + \gamma \frac{m^* n_{\bar{\sigma}}}{n n_\sigma e^2} & -\gamma \frac{m^*}{ne^2} \\ -\gamma \frac{m^*}{ne^2} & \frac{-i\omega m^*}{n_{\bar{\sigma}} e^2} + \frac{m^*}{n_{\bar{\sigma}} e^2 \tau_{\bar{\sigma}}} + \gamma \frac{m^* n_{\bar{\sigma}}}{n n_{\bar{\sigma}} e^2} \end{bmatrix} \quad (10)$$

Here, $\gamma \frac{m^*}{ne^2}$ is the spin coulomb drag resistivity.

Discussion

The matrix is symmetric and the off diagonal terms are negative. The minus sign can be easily explained. The transresistivity is induced in the up-spin channel by a current flowing in the down-spin channel when the up-spin current is zero. Since a down spin current in the positive direction tends to drag along the up-spin, a negative electric field is needed to maintain the zero value of the up-spin current. There is no limit on the magnitude of $\rho_{\sigma\bar{\sigma}}$. The only restriction is that the Eigen values of the real part of the resistivity matrix should be positive to ensure the positivity of the dissipation. Finally, the SCD appears in both diagonal and off-diagonal terms so the total contribution cancels to zero which satisfies equation (3), if the drift velocities of up and down spins are equal. We directly obtain:

$$\rho_{\sigma\bar{\sigma}} = -\gamma \frac{m^*}{ne^2} \quad (11)$$

i.e. spin-drag transresistivity $\rho_{\sigma\bar{\sigma}}$ is directly proportional to the spin-drag co-efficient γ. Also the transresistivity is seen to be independent of the density of either spins rather it is inversely proportional to the total spin density inclusive of both the spins. In Fig. 1 $|\rho_{\sigma\bar{\sigma}}(\omega = 0, T)|$ as a function of the temperature, for $n_\sigma = n_{\bar{\sigma}}$ and in the density range $1 < r_s < 7$ is plotted. Where, r_s is usual electron gas parameter.

Figures: 1 In Fig. 1 $|\rho_{\sigma\bar{\sigma}}(\omega = 0, T)|$ as a function of the temperature, for $n_\sigma = n_{\bar{\sigma}}$ and in the density range $1 < r_s < 7$ is plotted. Where, r_s is usual electron gas parameter. The figure shows that, for metallic densities correspondent to $r_s \geq 5$and temperatures of the order of 40-60 K (at which, experiments on spin relaxation time using spin-polarized currents have been performed), the spin *trans*-resistivity is appreciable.

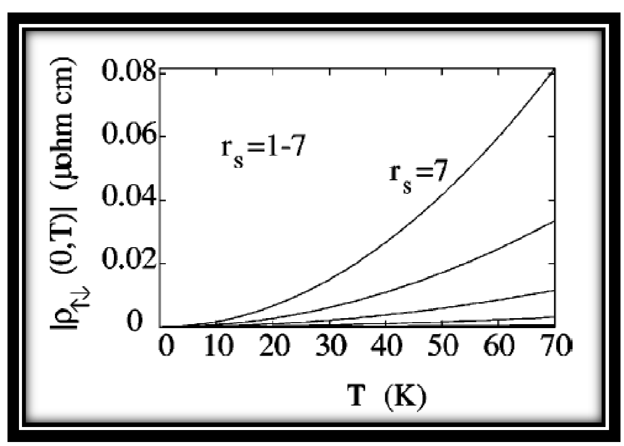

FIG. 1: Temperature and density dependence of $|\rho_{\sigma\bar{\sigma}}(0,T)|$ in a paramagnetic metal. (Courtesy: *Phys. Rev.* B-62,4853(2000))

The figure shows that, for metallic densities correspondent to $r_s \geq 5$and temperatures of the order of 40-60 K (at which, experiments on spin relaxation time using spin-polarized currents have been performed), the spin *trans*-resistivity is appreciable [1].

In a recent study [6], spin-drag transresistivity $\rho_{\sigma\bar{\sigma}}(\omega;\, n_\sigma, n_{\bar{\sigma}})$ as a function of frequency have been calculated for GaAs. This is illustrated in figure 2 which is a plot of spin-drag transresistivity $\rho_{\sigma\bar{\sigma}}(\omega;\, n_\sigma, n_{\bar{\sigma}})$ as a function of frequency for GaAs at T=0. It shows that $\rho_{\sigma\bar{\sigma}}$ has a maximum when Fermi energy E_F is of the order of $\hbar\omega$ which is reasonable to expect a sizable damping effect due to SCD. This is in agreement with the fact that SCD is a damping effect for spintronic systems

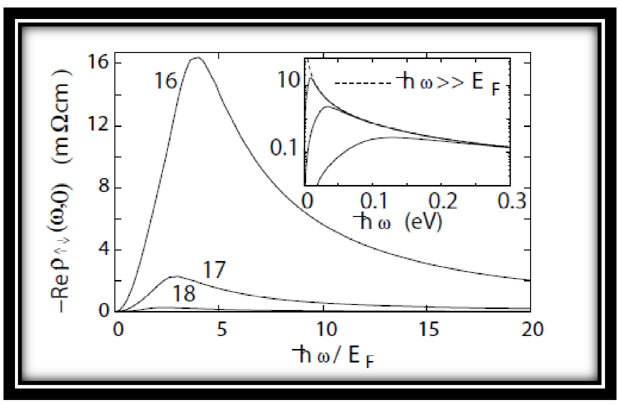

FIG. 2 spin-drag transresistivity $\rho_{\sigma\bar{\sigma}}(\omega;\, n_\sigma, n_{\bar{\sigma}})$ as a function of frequency for GaAs at T=0 (Courtesy: *Phys. Rev.* B-74, 121303(2006))

Weber et al [7] have experimentally observed that over a broad range of temperature and electron density, the flow of spin polarization in a two dimensional electron gas is controlled by the rate of electron- electron (e-e) collision, Whereas in the description of charge transport the e-e scattering may be ignored, because the total momentum is conserved in this case. It has been shown that the SCD, due to its intrinsic mechanism for spin-polarized currents, is a source of power loss in spintronic devices. It is desirable that $\rho_{\sigma\bar{\sigma}}$ should be made as small as possible. From equation (11) we note that to reduce the trans-resistivity the density of conduction electrons should be made high. This can be accomplished in semiconductors by high doping.

Conclusions

From our theoretical analysis it is seen that the spin-flip process whether it is present or not does not affect the phenomenon of SCD. Since the SCD is known as a cause for decay mechanism for spin-polarized currents, it is known as a source for power loss in a spintronic device. It reduces the spin diffusion constant in comparison to the conventional density diffusion constant. In this way it enlarges the time during which a spin packet can be controlled. A noticeable reduction in the spin-diffusion constant was measured [7] and found to be in agreement with the SCD reduction calculated for a two dimensional electron gas. It is also shown [8] that even when other forms of damping, such as disorder and phonons are drastically reduced by careful selection of the system characteristics, the dissipation induced by SCD cannot be avoided due to its intrinsic nature. Recent years have seen an upsurge of research in Diluted Magnetic Semiconductor (DMS) materials due to their application in spintronic devices [9]. A number of such devices are under development. Some researchers are working in this field and trying to develop some suitable materials with ferromagnetic properties [10,11]. Ferromagnetic semiconductors are major requirement for spintronics. So, it is now a challenge to science community to find out the ways to suppress the SCD effect so that the new generation device with high memory and storage capacity can be built.

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