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Abstract
We analyse the combined effect of high electric field and Coulomb
interaction on spin transport in semiconductors. We concentrate on the
experimentally relevant regime characterized by $T \lesssim T_F$ (*intermediate to
degenerate*), where $T_F = \varepsilon_F/k_B$ is the Fermi temperature. By the careful
analysis of the downstream spin diffusion length L_d, we (i) demonstrate that
in this regime carrier–carrier interactions become important and (ii)
introduce the 'semiconductor degenerate' regime, in which spin-transport
properties of a *degenerate* semiconductor are substantially modified by
applying a modest electric field. Finally we discuss how the electric field
and Coulomb interaction concur to influence the magnetoresistance of a
trilayer system.

Spin injection from a ferromagnet into a paramagnetic
semiconductor remains one of the challenges in semiconductor
spintronics [1]. Recently Yu and Flatté have pointed out
[2] that in lightly doped non-degenerate semiconductors
the efficiency of spin injection can be highly enhanced by
the application of a relatively modest electric field. In
addition to enhancing the 'downstream' diffusion length,
such an electric field can also substantially reduce the
magnetoresistance observed in ferromagnet–semiconductor–
ferromagnet structures [2].

In this work, we analyse spin transport in semiconductors
in the regime characterized by $T \lesssim T_F$ (*intermediate to
degenerate*), where $T_F = \varepsilon_F/k_B$ is the Fermi temperature.
Such regime is of great importance since it includes the lightly
doped semiconductor structures used in most experiments [3].

Following the derivation we proposed in section 5 of [4]
and imposing the steady-state condition $\partial(\Delta n_\uparrow - \Delta n_\downarrow)/\partial t =
0$ we obtain the steady-state *interacting* drift–diffusion
equation

$$-\frac{(\Delta n_\uparrow - \Delta n_\downarrow)}{\tau_s} + D_s \nabla^2(\Delta n_\uparrow - \Delta n_\downarrow)$$
$$+ \mu_s \mathbf{E} \cdot \boldsymbol{\nabla}(\Delta n_\uparrow - \Delta n_\downarrow) = 0, \qquad (1)$$

where $\tau_s = (1/\tau_{sf,\uparrow} + 1/\tau_{sf,\downarrow})^{-1}$ is the spin relaxation time, $\mathbf{E}$
the applied electric field, $\Delta n_\alpha(\mathbf{r}, t) \equiv n_\alpha(\mathbf{r}, t) - n_\alpha^{(0)}$, $n_\alpha(\mathbf{r}, t)$

the α density component, $n_\alpha^{(0)}$ its equilibrium value and
the effective *interacting* mobility and diffusion constants
are given [4], in the paramagnetic case, by $\mu_s = e\tau_D/m^*$
and $D_s = (\mu_s k_B T/e)(S/S_c)/(1 - \rho_{\uparrow\downarrow}/\rho_D)$. Here ρ_D is
the ordinary Drude resistivity, S the static longitudinal spin
stiffness ($S = \partial^2 f/\partial(n_\uparrow - n_\downarrow)^2$, with f the free energy per
unit volume of a homogeneous interacting electron gas), S_c
its classical counterpart, and $\rho_{\uparrow\downarrow}$ the spin transresistivity. The
spin transresistivity $\rho_{\uparrow\downarrow}(T)$ can be defined as the ratio of the
gradient of the electrochemical field for up-spin electrons ($E_\uparrow$)
to the current of down-spin electrons ($j_\downarrow$) when the current of
up-spin electrons is zero:

$$E_\uparrow = \rho_{\uparrow\downarrow}(T)j_\downarrow, \qquad (j_\uparrow = 0). \qquad (2)$$

$\rho_{\uparrow\downarrow}(T)$ measures the momentum rate exchanged between spin-
up and spin-down carriers [4, 5].

In the paramagnetic limit, Coulomb interactions enter
equation (1) through the diffusion constant. We want to
point out that the experimentally important regime $T \lesssim T_F$ is
the same in which Coulomb interactions between carriers of
opposite spin can become relevant. They enter D_s by affecting
the spin stiffness S and generating the spin transresistivity $\rho_{\uparrow\downarrow}$
[4, 5]: for $T \sim T_F$ the spin transresistivity has its maximum
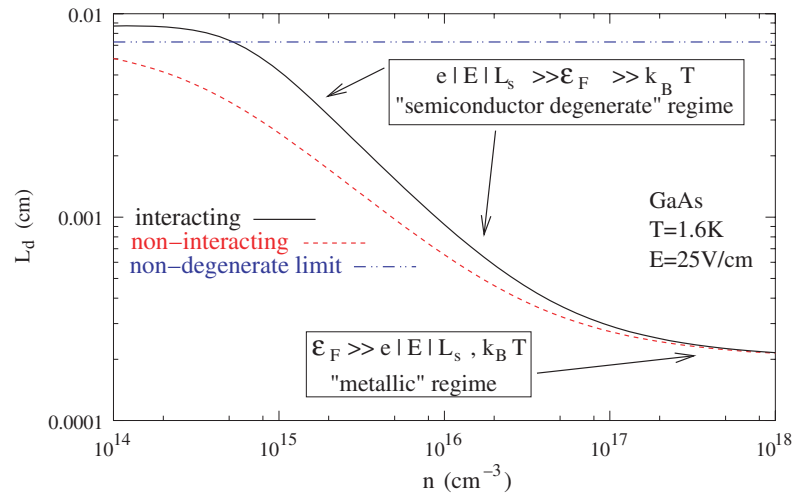and can become of the same order as the Drude resistivity [4],

Figure 1. Downstream diffusion length L_d versus carrier density. The figure shows that even in the degenerate regime, a modest field can heavily modify L_d. In the same range of densities the effect of carrier–carrier interaction can more than double the value of L_d.

while for $T \lesssim T_F$ the spin stiffness displays the maximum deviation from its non-interacting approximation [4]. These two combined effects can *reduce* the non-interacting approximation to D_s even by 50% [4]; according to their D_s dependence, Coulomb interaction effects may get amplified as it is the case for the downstream spin-diffusion length (see figure 1).

In one dimension the solution to equation (1) is $\Delta n_\uparrow - \Delta n_\downarrow = A\, e^{x/L_u} + B\, e^{-x/L_d}$ with

$$L_{u,d} = \left[\pm \frac{\mu_s|E|}{2D_s} + \sqrt{\left(\frac{\mu_s|E|}{2D_s}\right)^2 + \frac{1}{D_s\tau_s}} \right]^{-1} \quad (3)$$

the *interacting* upstream (L_u, 'plus' sign) and downstream (L_d, 'minus' sign) 'diffusion' lengths. L_d (L_u) represents the carrier penetration length along (opposite to) the number current density direction. Again we note that in paramagnets Coulomb interactions enter $L_{u,d}$ through D_s.

Let us consider a n-doped GaAs sample at $T = 1.6$ K, and focus on the crossovers undergone by the system when the carrier density is increased keeping the applied electric field fixed. At this temperature, even at very low densities the system is degenerate ($\varepsilon_F \gg k_BT$), so it is interesting to study the interplay between the Fermi energy and the electric field related energy $e|E|L_s$, where $L_s = \sqrt{\tau_s D_s}$ is the spin-diffusion length. As shown in the figure, depending on the system density, the Fermi energy can be low enough to enter, even for moderate electric fields, the 'semiconductor degenerate regime' $e|E|L_s \gg \varepsilon_F$. The existence of such a regime implies that, *even for a degenerate system*, the drift term in equation (1) cannot be neglected, i.e. it is not possible to describe spin transport using a diffusion equation for the electrochemical potentials, as usually done for metals [6]. Even in *degenerate* semiconductor systems in fact, the drift term severely modifies the penetration lengths $L_{u,d}$, varying their values over order of magnitudes (as clearly shown for L_d in figure 1). The 'semiconductor degenerate' regime extends to higher densities when the applied field is increased. Note that, even in such regime, the actual value of L_d strongly differs from its non-degenerate limit. By increasing the carrier
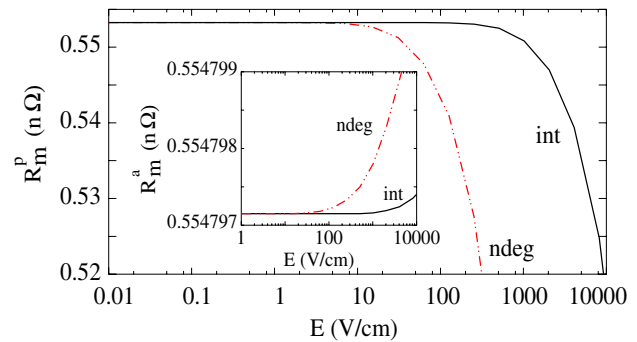
Figure 2. Main panel: magnetoresistance R_m for the *parallel* configuration versus electric field for $p_f = 0.5$. Its non-degenerate approximation (dashed-double-dot line) is plotted for comparison. Inset: as for main panel, but for the *antiparallel* configuration.

density, the system will eventually enter the 'metallic' regime (as indicated in the figure), in which the drift term can be neglected and $L_{u,d}$ recover their unperturbed value L_s.

In figure 1, we plot also the non-interacting approximation to L_d (dashed line). As one can see, the correction can be of the order of 100%, definitely non-negligible when quantitative calculations are required. Similarly Coulomb interactions influence the behaviour of the upstream diffusion length L_u (not shown here), with the key difference that L_u is *reduced* by Coulomb interactions. Since key quantities such as the spin current polarization and the magnetoresistance are functions of L_u and L_d [2, 3], their values will be consequently affected by electron–electron Coulomb interactions.

As an example, figure 2 illustrates the behaviour of the magnetoresistance R_m as a function of the electric field for a ferromagnetic/non-magnetic/ferromagnetic (FM) structure. The non-magnetic material is n-doped GaAs; the parameters are $n = 5 \times 10^{16}$ cm^{-3}, FM–semiconductor conductivity ratio $\sigma^f/\sigma_{sc} = 100$, FM spin diffusion length $L_f = 20$ nm, $L_s = 2\,\mu$m, $T = 1.6$ K and FM polarization $p_f = 0.5$. The main panel refers to the configuration in which the two FM magnetizations are parallel. We clearly see that the field decreases the magnetoresistance. The

opposite trend occurs when the magnetization of one FM is reversed: our calculations show that in the *antiparallel* case the magnetoresistance is *increased* by the applied electric field (see inset). In both cases, the non-degenerate approximation (dashed double-dot line) is shown for comparison and it clearly overestimates the field effect. For the carrier density and temperature considered, the Coulomb corrections to the non-interacting approximation are of the order of 20–25% (not shown).

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