Spin diffusion in doped semiconductors

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Abstract

The behavior of spin diffusion in doped semiconductors is shown to be qualitatively different than in undoped (intrinsic) ones. Whereas a spin packet in an intrinsic semiconductor must be a multiple-band disturbance, involving inhomogeneous distributions of both electrons and holes, in a doped semiconductor a single-band disturbance is possible. For n-doped nonmagnetic semiconductors the enhancement of diffusion due to a degenerate electron sea in the conduction band is much larger for these single-band spin packets than for charge packets, and can exceed an order of magnitude at low temperatures even for equilibrium dopings as small as $10^{16}$ cm$^{-3}$. In n-doped ferromagnetic and semimagnetic semiconductors the motion of spin packets polarized antiparallel to the equilibrium carrier spin polarization is predicted to be an order of magnitude faster than for parallel polarized spin packets. These results are reversed for p-doped semiconductors.
The motion and persistence of inhomogeneous electronic distributions are central to the
electronic technologies based on semiconductors. Recently a broader category of possible
disturbances, namely those involving inhomogeneous spin distributions in doped semicon-
ductors, have been shown to exhibit long lifetimes [1–3] and anomalously high diffusion rates
[3]. This behavior indicates the potential of a new electronic technology [4] relying on spin.
A crucial requirement of this new technology, however, is the clarification of the transport
properties of inhomogeneous spin distributions. [1] A full understanding is also desirable
of the relationship between the physical effects driving semiconductor spin electronics and
those driving the mature area of metallic spin electronics, [6] which has produced advances
in magnetic read heads and non-volatile memory.

These spin distributions are also of fundamental interest as well, for they are phase-
coherent states which can be very long lived (> 100 ns) and very extended (> 100 µm).
In contrast to phase-coherent ground states, such as the BCS ground state of a supercon-
ductor or the Laughlin state of the fractional quantum hall system, these spin distributions
are nonequilibrium phase-coherent states. Their long lifetime and large spatial size allow
unprecedented probes of phase-coherent behavior — of which Refs. [2,3] are initial examples.

We consider the properties of doped and undoped semiconductors which are unpolarized
in equilibrium but have a localized perturbation of the carriers. In the highly-doped limit
this system should behave like a paramagnetic metal (such as the copper used in Co/Cu
multilayer giant magnetoresistive devices [7]). Qualitative differences in diffusion are found
between the doped and undoped systems, at doping densities of $10^{16}$ cm$^{-3}$ at low temper-
ature and $10^{18}$ cm$^{-3}$ at room temperature. Quantitative agreement is found with recent
experimental results on rapid spin diffusion at low temperature. [3] We also describe spin
diffusion in spin polarized semiconductors. This work may assist in understanding spin
transport within metallic ferromagnetic semiconductors, such as GaMnAs, [8] which has
been used in spin-dependent resonant tunneling devices, [9] and semimagnetic semiconduc-
tors, such as BeMnZnSe, [10] which has been used in a spin-polarized light-emitting diode.
[11]

The origin of the differences in spin diffusion between semiconductors and metals are (1)
the much greater spin relaxation lifetime in semiconductors, (2) the relative ineffectiveness of
screening in semiconductors relative to metals, and (3) the possibility of controlling whether
carriers in a band are degenerate or not by small perturbations (e.g. electric fields or
doping). The first of these differences was explored in Ref. [5]. In this letter we examine
the implications of the second and third aspects. We show that careful consideration of the
consequences of (2) and (3) lead to a direct explanation of the anomalously high diffusion
rates of spin packets observed in Ref. [3]. The effect of the metal-insulator transition on spin
diffusion, which can be substantial in semiconductors, [12] is judged in this circumstance to
be small.

Ineffective screening in semiconductors requires that local variations in the conduction
electron density ($\Delta n(x)$) be, under normal circumstances, balanced by a local change in
the valence hole density ($\Delta p(x)$). Even small local variations of charge in a semiconductor
produce large space-charge fields which force the system to approximate local neutrality.
In metals, by contrast, local charge density variations are screened out on length scales
of Angstroms. The $\Delta n(x) \sim \Delta p(x)$ constraint in semiconductors has key implications for
the motion of packets of increased carrier density. [13,14] If such a packet moves, both the

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conduction electrons and valence holes which comprise it must move together. The motion of holes in semiconductors tends to be much slower (due to their lower mobility) than that of electrons, so hole mobility and diffusion tends to dominate the properties of a packet consisting of both electron and hole density variations.

Spin packets in semiconductors are also subject to these constraints. Consider a spin packet which involves an increase in the density of spin-up electrons, or \( \Delta n_\uparrow(x) > 0 \). In undoped semiconductors it is not possible for the population of the other spin species to be substantially decreased, for the thermally generated background of conduction electrons is quite small. Hence an increase in the population of one spin species of carrier implies an increase in the total population of that carrier, so \( \Delta n_\uparrow(x) > 0 \) implies \( \Delta n(x) > 0 \). The increase in the total electron density then implies a local increase in the hole density to maintain \( \Delta n(x) \sim \Delta p(x) \). Even if the holes in the packet are not spin polarized themselves, their presence affects the motion of the spin-polarized electrons.

In a doped semiconductor, however, there is a substantial background of conduction electrons, so \( \Delta n_\downarrow(x) \) can be significantly less than zero. Thus one can create a spin packet through a spin imbalance in the conduction band (\( \Delta n_\downarrow(x) = -\Delta n_\uparrow(x) \)), without excess electrons or holes (\( \Delta n(x) = 0 = \Delta p(x) \)). This spin packet does not drag a local inhomogeneous hole density with it, and thus its mobility and diffusion properties are very different from those of a spin packet in the undoped semiconductor.

The two situations are distinguished in Fig. 1 for a nonmagnetic electron-doped material. Figure 1(a) shows an inhomogeneous electron-hole density in the form of a spatially localized packet. This disturbance, which we will refer to as a charge polarization packet (or charge packet), could be created optically, in which case the excitation process guarantees \( \Delta n(x) = \Delta p(x) \), or by electrical injection, in which case space charge fields force \( \Delta n(x) \sim \Delta p(x) \). This type of disturbance is thus fundamentally multiple-band. Figure 1(b), however, shows a spin disturbance within the conduction band, which is an enhancement of the density of spin-up electrons and a corresponding reduction of the density of spin-down electrons (\( \Delta n_\downarrow(x) = -\Delta n_\uparrow(x) \)). There is no corresponding inhomogeneity in the hole density (\( \Delta p_\downarrow(x) = \Delta p_\uparrow(x) = 0 \)), so the disturbance in essence only involves a single band. This type of disturbance will be referred to as a spin polarization packet, or a spin packet.

As described and demonstrated in Ref. [2], generation of this spin packet can be performed optically with circularly polarized light in a system where the spin relaxation time for holes is short, and for electrons is long, relative to the recombination time. Shortly after the excitation process creates spin-polarized electrons and holes, the holes lose their spin polarization. During the recombination process the unpolarized holes annihilate an equal number of spin up and spin down electrons, leaving behind excess spin polarization in the conduction band.

We now describe the implications for mobility and diffusion of these two types of packets. The motion of a charge packet (Fig. 1(a)) involves dragging both a conduction and valence disturbance, and is described by an ambipolar mobility and diffusion constant,

\[
\mu_a = \frac{(n - p)\mu_e\mu_h}{n\mu_e + p\mu_h},
\]

\[
D_a = \frac{n\mu_eD_h + p\mu_hD_e}{n\mu_e + p\mu_h},
\]

where \( D_e, \mu_e \) and \( D_h, \mu_h \) are the diffusion constants and mobilities for electrons and holes
respectively. For \( n \)-doping (\( n \gg p \)), \( D_a \sim D_h \) and \( \mu_a \sim \mu_h \), so diffusion and mobility of the charge packet is dominated by the holes. The mobility and diffusion constants of the spin packet of Fig. 1(b), however, are

\[
\mu_s = \frac{(n_\downarrow + n_\uparrow)\mu_{e\downarrow}\mu_{e\uparrow}}{n_\downarrow\mu_{e\downarrow} + n_\uparrow\mu_{e\uparrow}},
\]

\[
D_s = \frac{n_\downarrow\mu_{e\downarrow}D_{e\downarrow} + n_\uparrow\mu_{e\uparrow}D_{e\uparrow}}{n_\downarrow\mu_{e\downarrow} + n_\uparrow\mu_{e\uparrow}},
\]

where we now allow the different spin directions to have different mobilities and diffusion constants.

For the nonmagnetic semiconductor of Ref. [3], with \( n_\uparrow = n_\downarrow \), \( \mu_{e\uparrow} = \mu_{e\downarrow} \), and \( D_{e\uparrow} = D_{e\downarrow} \), the mobility and diffusion constants of the spin packet are merely the electron mobility \( \mu_e \) and diffusion constant \( D_e \). Thus the mobility of the spin packet is predicted to be the same as that measured in transport. The importance of the metal-insulator transition can be estimated by considering \( \sigma(L) \), the dependence of conductivity on the physical length scale probed. [12] In Ref. [3] the mobility measured optically over a distance of microns was seen to be comparable to the mobility from transport measurements through the entire sample, suggesting that the material was not sufficiently close to the metal-insulator transition to exhibit significant effects on the conductivity on these length scales.

Because the diffusion and mobility of spin and charge packets in doped semiconductors are determined by the properties of a single carrier species, we can relate the mobility \( \mu \) of a packet to the diffusion constant \( D \) describing the spread of the packet with an expression derived for a single species,

\[
qD = -\mu \frac{\int_0^\infty N(E)f_o(E) dE}{\int_0^\infty N(E)(\partial f_o(E)/\partial E) dE}.
\]

Here \( N(E) \) is the density of states of the band with the zero of energy chosen so that the band edge is \( E = 0, f_o(E) \) is the Fermi function, and \( q \) is the charge of the species. In the low density limit \( (\partial f_o(E)/\partial E) = f_o(E)/kT \), where \( T \) is the temperature and \( k \) is Boltzmann’s constant, and so \( eD = \mu kT \), which is Einstein’s relation.

Figure 2 shows \( eD/kT\mu \) for a spin packet (solid line) and a charge packet (dashed line) in \( n \)-doped GaAs at \( T = 1.6K \). The relevant mobility and diffusion constant for the spin packet are those of the conduction electrons, while those for the charge packet are those of the valence holes. This enhancement over the Einstein relation is directly attributable to Fermi pressure, that is, the faster increase of the chemical potential with density for a degenerate Fermi gas relative to a non-degenerate Fermi gas. For a given gradient in the density of the degenerate Fermi gas, a larger gradient in the chemical potential results, yielding faster diffusion.

Fermi pressure is substantially more important for spin packets than for charge packets, which exhibit the effect at densities closer to \( 10^{18} \text{ cm}^{-3} \) at low temperature, and may require densities as high as \( 10^{20} \text{ cm}^{-3} \) at room temperature. At higher temperatures it also requires considerably higher densities for Fermi pressure to play a significant role in spin packet diffusion, but the densities are still achievable, corresponding to \( 10^{18} \text{ cm}^{-3} \). The quantitative difference in the significance of Fermi pressure for spin packets, which are dominated by
conduction electron properties, and for charge packets, which are dominated by valence hole properties, occurs because the conduction band has a density of states \( (m_e/m_h)^{3/2} \sim 0.045 \)
smaller than the valence band in GaAs and therefore becomes degenerate at lower density. At \( 10^{16} \text{ cm}^{-3} \) the enhancement over the Einstein relation is 12, which is in good agreement with the “more than one order of magnitude” enhancement seen in Ref. [3].

In order to generate spin packets in a \( p \)-doped semiconductor the time scales of spin decoherence in the conduction and valence band would need to be different, but perhaps a semiconductor will be found where this is possible. In this case it is the charge packet which is dominated by the diffusion and mobility properties of the conduction electrons, whereas the spin packet is dominated by the properties of the valence holes. Thus the charge packet is over an order of magnitude more mobile than the spin packet, precisely the opposite case as for an \( n \)-doped semiconductor.

We now turn to the behavior of spin and charge packets in a spin-polarized semiconductor, where equilibrium densities, mobilities and diffusion constants can differ for the two spin densities. Our first specific example will be an \( n \)-doped spin-polarized semiconductor (such as BeMnZnSe) which we assume is 100% spin polarized at the chemical potential. We note that the spin splitting required to achieve this polarization in a semiconductor, where typical Fermi energies are \( 10^{-2} \text{ to } 100 \text{ meV} \), is much less than that required in a metallic system. For this semiconductor in equilibrium \( n_\uparrow > 0 \), but \( n_\downarrow, p_\uparrow, \) and \( p_\downarrow \) are all approximately zero.

As shown in Fig. 3 a single-band spin polarization packet is only possible for a spin packet polarized antiparallel to the equilibrium carrier spin polarization. This restriction occurs because \( \Delta n_\uparrow(\mathbf{x}) < 0 \) is possible, but not \( \Delta n_\downarrow(\mathbf{x}) < 0 \). Thus a packet with spin polarized parallel to the equilibrium spin (Fig. 3(a)) must consist of both electron and hole perturbations \( \Delta n_\uparrow(\mathbf{x}) > 0 \) and \( \Delta p(\mathbf{x}) > 0 \) and would have diffusion and mobility properties dominated by the minority holes. The antiparallel spin packet (Fig. 3(b)), however, can be a single band disturbance with \( \Delta n_\uparrow(\mathbf{x}) < 0 \) and \( \Delta n_\downarrow(\mathbf{x}) > 0 \). Such a spin packet would have diffusion and mobility properties entirely determined by those of the majority electrons, and thus over an order of magnitude faster. We show in Fig. 4 the different ratios of diffusion constant to mobility for spin packets polarized parallel and antiparallel to the equilibrium carrier spin polarization.

The behavior of spin packets in a \( p \)-doped spin-polarized semiconductor, such as GaMnAs, is completely the opposite. Here a spin packet polarized parallel to the equilibrium carrier spin polarization would require a conduction electron component. The minority carriers (the electrons) would determine the mobility and diffusion constant of such a packet. A spin packet polarized antiparallel to the equilibrium carrier spin polarization could consist entirely of holes, however, and would have a much smaller mobility and diffusion constant. This qualitative difference in the diffusion and mobility of spin polarization packets in the \( n \) and \( p \)-doped semiconducting systems should have technological implications for spin electronic devices.

We conclude with a brief comment on the behavior of spin distributions in inhomogeneous semiconductors compared to those in metallic ferromagnets. As pointed out in Ref. [16], in metallic ferromagnets the short-distance physics of screening can be entirely separated from the physics of spin populations by writing a drift-diffusion equation for the chemical potential rather than the density. This separation depends on the linear dependence of the density on the chemical potential in these systems. This relationship does not hold in
semiconductors and the separation of the screening length scale from the spin distribution length scale is no longer possible. Thus the exploration of spin transport in inhomogeneously doped spin-polarized semiconductor materials should yield a rich range of behavior distinct from metallic systems.

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FIGURES

FIG. 1. Spin subband profile of charge and spin polarization packets in a semiconductor. Space charge constraints require $\Delta n(x) \sim \Delta p(x)$, so a charge disturbance in the conduction band requires a corresponding disturbance in the valence band. In contrast, a pure spin disturbance can exist in the conduction band of a doped semiconductor without any disturbance in the valence band.

FIG. 2. Ratio of diffusion to mobility for charge (dashed) and spin packets (solid) in GaAs at 1.6K and 300K as a function of background conduction electron ($n$) density. The diffusion and mobility of the charge packet is dominated by the valence holes, whereas that of the spin packet is dominated by the conduction electrons.

FIG. 3. Spin subband profile of spin polarization packets polarized parallel and antiparallel to the equilibrium carrier spin polarization of an $n$-doped spin-polarized semiconductor.

FIG. 4. Ratio of diffusion to mobility for spin packets polarized parallel (dashed) and antiparallel (solid) to the equilibrium carrier spin polarization of the semiconductor Be$_x$Mn$_y$Zn$_{1-x-y}$Se at 1.6K and 30K as a function of conduction electron density (Be doping). The conduction mass is 0.16$m_o$ and the heavy hole mass is 0.74$m_o$, where $m_o$ is the free mass. [10]
(a) Charge packet

\[
\begin{align*}
n_\uparrow & \quad \text{Position} \\
n_\downarrow & \\
p_\uparrow & \\
p_\downarrow &
\end{align*}
\]

(b) Spin packet

\[
\begin{align*}
& \\
& \\
& \\
&
\end{align*}
\]
(a) Parallel

(b) Antiparallel

\[ \text{Position} \]
