Spin Diffusion in Semiconductors

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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—this explains the anomalously large spin diffusion recently observed in n-doped GaAs at 1.6 K. 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.

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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 semiconductors, has been shown to exhibit long lifetimes (>100 ns) [1–3] and anomalously high diffusion rates [3]. In addition to allowing new probes of nonequilibrium phase coherence, 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 [5]. 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 nonvolatile memory.

We consider the properties of doped and undoped semiconductors which are unpolarized in equilibrium but have a localized perturbation of spin-polarized 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]). The spin polarized perturbation can be created optically with circularly polarized light or electrically (e.g., with a spin filter [8]). Enhanced diffusion due to electron degeneracy is found to explain the order of magnitude larger than expected diffusion constant in n-doped GaAs at 1.6 K [3].

We also describe spin diffusion in spin-polarized semiconductors. The diffusion and mobility of spin packets are found to differ by orders of magnitude depending on whether they are polarized parallel or antiparallel to the spin polarization of the equilibrium carriers. This work may assist in understanding spin transport within metallic ferromagnetic semiconductors, such as GaMnAs [9], and semimagnetic semiconductors, such as BeMnZnSe [10]. Both the p-doped GaMnAs and the n-doped BeMnZnSe have been used in spin-dependent devices [11–13].

The origins of the differences in spin diffusion between semiconductors and metals are (i) the much greater spin relaxation lifetime in semiconductors, (ii) the ineffectiveness of screening in semiconductors relative to metals, and (iii) 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 Refs. [1,2]. Here we show that consideration of the consequences of (ii) and (iii) explains the anomalously high diffusion rates of spin packets observed in Ref. [3].

Ineffective screening in semiconductors requires local variations in the conduction electron density $[\Delta n(\mathbf{x})]$ to be balanced by a local change in the valence hole density $[\Delta p(\mathbf{x})]$. Exceptions require large space-charge fields, such as occur when donor or acceptor concentrations vary substantially. In metals, by contrast, local charge density variations are screened out on length scales of angstroms. The $\Delta n(\mathbf{x}) \sim \Delta p(\mathbf{x})$ constraint in semiconductors has key implications for the motion of packets of increased carrier density [14,15]. If such a packet moves, both the 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 tend to dominate the properties of a packet consisting of both electron and hole density variations. In the absence of spin polarization this disturbance is referred to as a charge packet [shown in Fig. 1(a) for an n-doped system].

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 $\Delta n_{\uparrow}(\mathbf{x}) > 0$. In undoped semiconductors it is not possible for the

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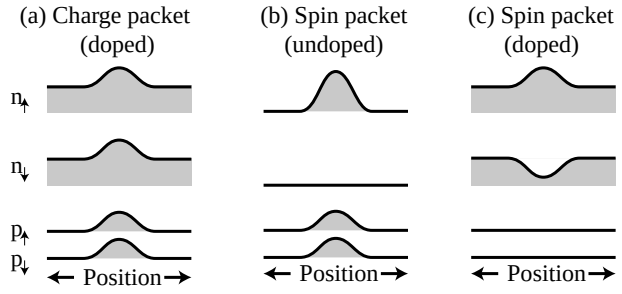

FIG. 1. Spin subband density profile of (a) charge polarization packets in an n-doped semiconductor, (b) spin polarization packets in an undoped semiconductor, and (c) spin polarization packets in an n-doped semiconductor.

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 a carrier implies an increase in the total population of that carrier, so $\Delta n_\uparrow(\mathbf{x}) > 0$ implies $\Delta n(\mathbf{x}) > 0$. The increase in the total electron density then implies a local increase in the hole density to maintain $\Delta n(\mathbf{x}) \sim \Delta p(\mathbf{x})$. This multiple-band disturbance is shown in Fig. 1(b). Even if the holes in the packet are not spin polarized themselves, their presence affects the motion of the spin-polarized electrons just as occurred in the charge packet.

In a doped semiconductor, however, there is a substantial background of conduction electrons, so $\Delta n_\downarrow(\mathbf{x})$ can be significantly less than zero. Thus one can create a spin packet through a spin imbalance in the conduction band $[\Delta n_\downarrow(\mathbf{x}) = -\Delta n_\uparrow(\mathbf{x})]$, without excess electrons or holes $[\Delta n(\mathbf{x}) = 0 = \Delta p(\mathbf{x})]$ [2]. This single-band spin packet [Fig. 1(c)] *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 perturbations in Figs. 1(a) and 1(b) decay with the carrier recombination time τ_r whereas that in Fig. 1(c) decays with the electron spin relaxation time $\tau_{s,e}$. We assume the spin relaxation time for holes $\tau_{s,h}$ is shorter than τ_r and $\tau_{s,e}$. As described and demonstrated in Ref. [2], generation of the spin packet in Fig. 1(c) can be performed optically with circularly polarized light in a system where $\tau_{s,h} \ll \tau_r \ll \tau_{s,e}$. In this limit 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. Also, for times longer than $\tau_{s,h}$, Figs. 1(a) and 1(c) can be considered elementary excitations of the doped system.

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 [15],

$$\mu_a = \frac{(n - p)\mu_e\mu_h}{n\mu_e + p\mu_h}, \qquad D_a = \frac{n\mu_e D_h + p\mu_h D_e}{n\mu_e + p\mu_h}, \tag{1}$$

where D_e, μ_e and D_h, μ_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 the diffusion and the mobility of the charge packet are dominated by the *holes*. The mobility and diffusion constants of the spin packet of Fig. 1(c), however, involve dragging only a spin-up and a spin-down conduction disturbance, so in analogy with the two-species case of Eqs. (1),

$$\mu_s = \frac{(n_\downarrow + n_\uparrow)\mu_{e\downarrow}\mu_{e\uparrow}}{n_\downarrow\mu_{e\downarrow} + n_\uparrow\mu_{e\uparrow}},$$
$$D_s = \frac{n_\downarrow\mu_{e\downarrow}D_{e\uparrow} + n_\uparrow\mu_{e\uparrow}D_{e\downarrow}}{n_\downarrow\mu_{e\downarrow} + n_\uparrow\mu_{e\uparrow}}, \tag{2}$$

where the two species are now spin up and down. For the nonmagnetic semiconductor of Ref. [3], with $n_\uparrow = n_\downarrow$, $\mu_{e\uparrow} = \mu_{e\downarrow}$, and $D_{e\uparrow} = D_{e\downarrow}$, Eqs. (2) predict $\mu_s = \mu_e$ and $D_s = D_e$. Thus the mobility of the spin packet is predicted to be the same as that of the electron sea background.

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 μ of a packet to the diffusion constant D describing the spread of the packet with an expression [15] derived for a single species,

$$eD = -\mu \frac{\int_0^\infty N(E) f_0(E)\, dE}{\int_0^\infty N(E)\,(\partial f_0(E)/\partial E)\, dE}, \tag{3}$$

$$= 2\mu kT \frac{F_{1/2}[E_F/kT]}{F_{-1/2}[E_F/kT]}. \tag{4}$$

Here $N(E)$ is the density of states of the band with the zero of energy chosen so that the band edge is $E = 0$, $f_0(E)$ is the Fermi function, and e is the magnitude of the charge of the species. Equation (3) comes from considering diffusion to be driven by a gradient in the chemical potential caused by the increase in density. Equation (4) holds for a bulk parabolic band, where $N(E) = (2E)^{1/2}m^{3/2}/(\pi^2\hbar^3)$ and $F_n(\xi) = \int_0^\infty x^n[\exp(x - \xi) + 1]^{-1}$. In the low density limit $[\partial f_0(E)/\partial E] = -f_0(E)/kT$, where T is the temperature and k is Boltzmann's constant, and so $eD = \mu kT$, which is Einstein's relation. For degenerate systems, however, $eD/kT\mu > 1$ because of the faster increase of the chemical potential with density (Fermi pressure). Whereas $eD/kT\mu$ is adjustable by light doping of a semiconductor, in a metal this value is more difficult to change [point (iii) above].

Figure 2 shows $eD/kT\mu$ obtained from Eq. (4) for a spin packet (solid line) and a charge packet (dashed line) in n-doped GaAs at $T = 1.6$ K. The quantitative difference in $eD/kT\mu$ for spin packets, which are dominated by conduction electron properties, and for charge packets, which

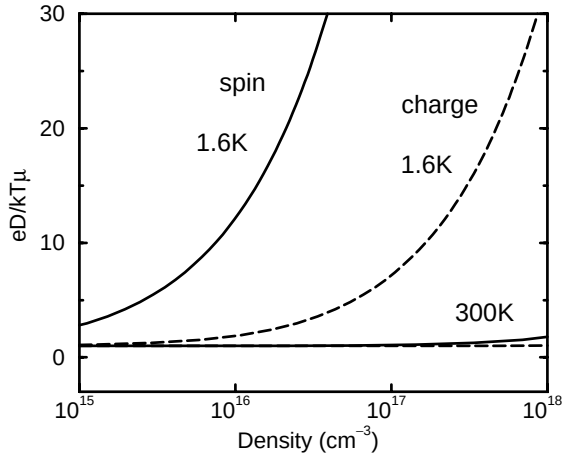

FIG. 2. (Solid line) Ratio of diffusion to mobility for spin packets in GaAs at 1.6 K and 300 K as a function of background conduction electron (n) density. (Dashed line) Same for charge packets as a function of *packet* density. The diffusion and the mobility of the charge packet are dominated by the valence holes, whereas those of the spin packet are dominated by the conduction electrons.

are dominated by valence hole properties, occurs because the conduction band electrons have a very different mass ($m_e = 0.067m_0$, where m_0 is the free electron mass) from the valence band holes ($m_h = 0.53m_0$), and $N(E) \sim m^{3/2}$. This mass dependence of $N(E)$ implies $eD/kT\mu \gg 1$ for spin packets (due to conduction band degeneracy) at much lower densities $[(m_e/m_h)^{3/2} \sim 0.045]$ than have been predicted for charge packets [16]. At $n = 10^{16}$ cm^{-3}, $eD/kT\mu \sim 12$, which is in good agreement with the "more than 1 order of magnitude" enhancement seen in Ref. [3]. We note that if the nearby metal-insulator transition were important in the spin diffusion one would expect a nontrivial dependence of the mobility on the physical length scale probed [17]. In Ref. [3], however, μ_s measured optically over a distance of microns was seen to be $\sim\mu_e$ from transport measurements through the entire sample.

In order to optically generate single-band spin packets in a p-doped nonmagnetic semiconductor one would need $\tau_{e,s} \ll \tau_r \ll \tau_{h,s}$, conditions which are challenging to realize. Reference [12], however, demonstrated electrically injected spin-polarized currents in p-doped GaAs. For the p-doped semiconductor the charge packet 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 for typical band-edge masses, 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. For example, consider a 100% spin-polarized n-doped semiconductor, such as BeMnZnSe, which has spin subbands split by sp-d exchange and is fully spin polarizable in $\sim$1 T [10]. For this semiconductor in equilibrium $n_\uparrow > 0$, but $n_\downarrow$, $p_\uparrow$, and $p_\downarrow$ are all approximately zero. Here $\uparrow$ is defined as the low-energy spin direction in the magnetic field. As shown in Fig. 3 a single-band spin polarization packet is possible only 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 $\Delta n_\downarrow(\mathbf{x}) > 0$. The same conditions described before for single-band packets in unpolarized doped semiconductors, $\tau_{s,h} \ll \tau_r \ll \tau_{s,e}$, are required to optically create these single-band antiparallel spin packets. Such a spin packet would have diffusion and mobility properties entirely determined by those of the majority electrons and thus would move 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. Here $N(E)$ is half that in the spin unpolarized state, $m_e = 0.16m_0$, and $m_h = 0.74m_0$ [10].

The behavior of spin packets in a spin-polarized p-doped semiconductor, such as ferromagnetic 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.

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. [18], in metallic ferromagnets the short-distance physics of screening can be entirely separated from the physics of spin populations by writing a drift-diffusion

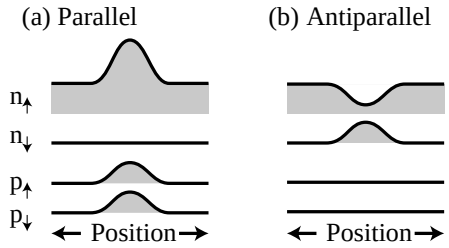

FIG. 3. Spin subband density profile of spin polarization packets polarized (a) parallel and (b) antiparallel to the equilibrium carrier spin polarization of an n-doped spin-polarized semiconductor.

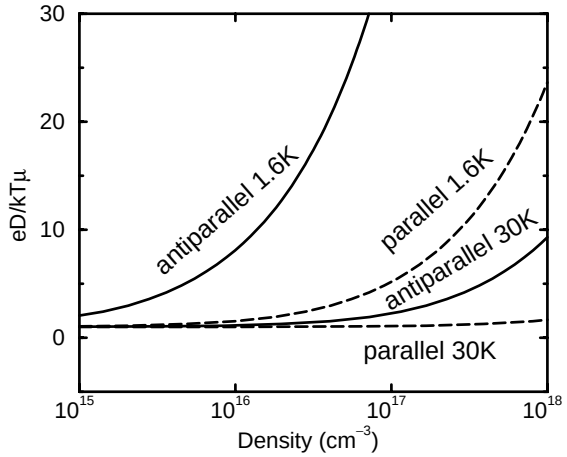

FIG. 4. (Solid line) Ratio of diffusion to mobility for spin packets polarized antiparallel to the equilibrium carrier spin polarization of the semiconductor $Be_xMn_yZn_{1-x-y}Se$ at 1.6 and 30 K as a function of conduction electron density (Be doping). (Dashed line) Same, but for parallel spin packets as a function of *packet* density.

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 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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