Spin Gunn Effect

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We predict that the flow of unpolarized current in electron-doped GaAs and InP at room temperature is unstable at high electric fields to the dynamic formation of spin-polarized current pulses. Spin-polarized current is spontaneously generated because the conductivity of a spin-polarized electron gas differs from that of an unpolarized electron gas, even in the absence of spin-orbit interaction. Magnetic fields are not required for the generation of these spin-polarized current pulses, although they can help align the polarization of sequential pulses along the same axis.

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Spin-based semiconductor electronics (“spintronics”) requires the generation of spin polarization in nonmagnetic semiconductors [1,2]. Approaches through the injection of spin-polarized electrons or holes from magnetic materials [3–7], and spin-filtered [8,9] or spin-selective [10–14] currents using the spin-orbit interaction have been considered. These rely on an energetic difference between spin-up and spin-down carriers in the same element of a circuit. Here we identify a different approach.

We show that initially unpolarized electron current flow in semiconductors can be unstable towards the spontaneous formation of spin-polarized current pulses even without an applied magnetic field. The mechanism we propose is related to the charge Gunn effect [15], in which homogeneous charge current flow is unstable to the spontaneous formation of high-electric-field domains, inhomogeneous charge distributions, and current pulses. We predict the “spin Gunn effect” can be seen at room temperature in GaAs and InP, and possibly [16] GaN. The dependence of the electron drift velocity on spin polarization—from the Pauli exclusion principle—drives the spin Gunn effect. A room-temperature source of spin-polarized electrons from a nonmagnetic semiconductor would significantly advance spintronic devices. The high-frequency oscillatory nature of these pulses suggests new possibilities, such as may be useful for spintronic devices. The high-frequency oscillatory nature of these pulses suggests new possibilities, such as may be useful for spintronic devices.

We consider a material in which a charge Gunn domain [15] has formed in the ordinary way. Thermal fluctuations lead to a small, randomly oriented spin polarization $P = (n_1 - n_2)/n$, where $n_1(n_2)$ is the density of spin-up (spin-down) electrons and $n = n_1 + n_2$. At room temperature a $P \approx 0.01\%$ in a small $(1 \mu m^3)$ region of GaAs doped to an electron density of $10^{18} \text{cm}^{-3}$ costs $k_B T$ to excite, where $k_B$ is the Boltzmann constant and $T$ the temperature. The application of an external magnetic field would preferentially orient these fluctuations antiparallel to the field (the $g$ factor for GaAs is $-0.44$ so a magnetic field of $0.2$ T would polarize spins $\sim 0.01\%$; a field of $0.5$ T would dominate over thermal fluctuations in a $1 \mu m^3$ region). Spin-orbit effects [17] could also seed the initial oriented spin polarization. Once $P \neq 0$, the amplifying effect described in this Letter causes it to grow until it reaches a saturation limit which can be near unity.

The amplification of this small initial spin polarization originates from an electron velocity ($\nu = \mu E$, where $\mu$ is the mobility and $E$ the electric field) that (1) depends on the local spin polarization of the electrons, and (2) differs for spin-up and spin-down electrons. The mobility depends on the carrier density, and thus the mobility for spin-up carriers, $\mu_1 = \mu(n_1)$, differs from that for spin-down carriers, $\mu_\downarrow = \mu(n_\downarrow)$. The mobility near $P = 0$ can be approximated as

$$\mu_\uparrow = \mu(n/2)(1 + (- \alpha P),$$

where

$$\alpha = \lim_{P \to 0} \frac{\mu_1 - \mu_\downarrow}{P\mu_{av}} = \lim_{P \to 0} \frac{\mu(n_1) - \mu(n_\downarrow)}{P\mu_{av}},$$

and $\mu_{av} = (n_1 \mu_1 + n_\downarrow \mu_\downarrow)/n$ is the average mobility. For a bulk parabolic band with effective mass $m^*$,

$$\mu_\uparrow = \frac{e}{m^*} \int_0^\infty e^{3/2} f_\uparrow(\epsilon) (\partial f_\uparrow(\epsilon)/\partial \epsilon) d\epsilon,$$

where $f_\uparrow(\epsilon)$ is the Fermi occupation function at energy $\epsilon$ of spin $\uparrow$, $\tau(\epsilon)$ is the carrier scattering time, and $e$ is the electron’s charge [18]. The dominant spin-conserving electron scattering mechanism, which determines $\tau(\epsilon)$ (tabulated in Ref. [18] for common mechanisms), determines the value of $\alpha$ we calculate below.

Most semiconductors have $\alpha \neq 0$. As shown in Fig. 1, due to the Pauli exclusion principle the chemical potentials of spin-up and spin-down electrons $[f_\uparrow(\epsilon)$ and $f_\downarrow(\epsilon)]$ in a spin-polarized electron gas are different. Thus in a polarized degenerate electron gas the energy distributions of spin-up and spin-down electrons differ, and the mobilities from Eq. (3) for $P \neq 0$ will differ from those for $P = 0$.

For scattering of conduction electrons from ionized impurities, acoustic phonons via piezoelectric coupling, or longitudinal phonons via Fröhlich coupling (LO-phonon
dependent mobility

dependence of carrier scattering that produces a density-

pendence of the mobility originates from the same energy

scattering processes themselves. The spin-polarization de-

even when there is no explicit spin dependence in the

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common scattering process that produces

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spin-polarization, see purple curve) than

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electrons. Calculations of the spin transresistivity in

GaAs and InP for

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(3), as a function of density at 300 and 500 K, and as a

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function of temperature for

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InP for

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n = 10^{18} \text{ cm}^{-3}. Green curves are LO-phonon scattering,

blue curves are ionized impurity scattering, red curves are

piezoelectric-phonon scattering, and black curves are DP-

phonon scattering.

We now consider the effect of \( \alpha \neq 0 \) on the spin polar-

ization of electrons in an initially unpolarized charge Gunn

domain. The Gunn domain itself moves in a self-sustaining

way—an inhomogeneous electric field moves the charge,

and the shifting space-charge region moves the electric

field—and the net result is the collective motion of the

electric field shape and the space-charge region through the

sample. A small difference in mobility between spin-up

and spin-down electrons means fewer electrons of one spin

species will flow in response to these electric fields. This

increase of \( P \) further enhances \( \mu_1 - \mu_1 \) (positive

feedback), which drives a further increase in \( P \). The electric

field is determined by the charge density through the

Poisson equation (independent of \( P \)), so the domain

continues to move as before but now with \( P \neq 0 \).

The very short (< 100 fs) electron momentum scattering

time permits use of drift-diffusion equations [1] to
calculate the time dependence of the spin polarization,

\[
\frac{\partial n_1}{\partial t} = -n_1 - n_3 - \frac{\partial (n_1 v_1)}{\partial x} + D_1 \frac{\partial^2 n_1}{\partial x^2},
\]

(4)

\[
\frac{\partial n_1}{\partial t} = -n_1 - n_3 - \frac{\partial (n_1 v_1)}{\partial x} + D_1 \frac{\partial^2 n_1}{\partial x^2},
\]

(5)

where \( T_1 \) is the spin relaxation time of the electrons and

\( D_1 \) are the diffusion constants for spin-up and spin-
down electrons, respectively. Using Eqs. (1)–(5), keeping

only terms up to first order in \( P \), neglecting pure diffusion

effects, and shifting to the domain’s frame (\( x' = x - v_{\text{dom}} t \),

where \( v_{\text{dom}} \) is the domain’s velocity),
\[
\frac{\partial P}{\partial t} = -\frac{\alpha}{n} \frac{\partial [nE\mu]}{\partial x'} P - \frac{P}{T_1} + \left[\mu(1 - \alpha)E - v_{dom}\right] \frac{\partial P}{\partial x'} \\
\sim \left( \gamma - \frac{1}{T_1} \right) P.
\]

This equation predicts spin amplification if \( \gamma > T_1^{-1} \). The \( \partial P/\partial x' \) term describes the flow of inhomogeneous spin polarization within the domain; similar terms describing charge flow are ignored in treating the charge Gunn effect itself [20], as they do not change any qualitative behavior. Our treatment here neglects this term, which we estimate to be over an order of magnitude smaller than \( \gamma P \).

The first observation about Eq. (6) is that the central quantity \( \gamma \) is proportional to the spatial variation of the drift current. \( \partial n_s/\partial t = \nabla \cdot j_s \), where \( j_s \) is the current of carriers with spin \( s \), so differing spin-up and spin-down currents (from \( \mu_1 \neq \mu_i \)) produce differing spin-up and spin-down density accumulation. \( \gamma \) is largest for situations involving large charge imbalances (yet still less than the material’s breakdown field). High doping levels produce more localized domains and less microwave power in the fundamental oscillation mode, so ordinary doping levels are in the range of \( 10^{13} - 10^{16} \) cm\(^{-3} \) for charge Gunn devices. For the spin Gunn effect, however, a higher density leads to larger \( P \).

We now quantitatively calculate the value of \( \gamma \) for a doping level of \( 10^{18} \) cm\(^{-3} \) at a 300 K lattice temperature in GaAs and InP. We ignore higher-order effects and evaluate \((\alpha/n)\partial [nE\mu(n/2)]/\partial x'\) for \( P = 0 \). Hence

\[
\gamma = -\alpha \mu E \left[ \frac{e(n - n_0)}{\epsilon_s E} + \frac{n}{\mu} \frac{\partial \mu}{\partial x'} + \frac{1}{\mu} \frac{\partial \mu}{\partial x'} \right]
\]

where \( \epsilon_s \) is the dielectric permittivity of the semiconductor. Our calculation of \( n(x') \) and \( E(x') \) for the Gunn domain follows that of Sze [21] for a mature, steady-state domain. We assume the electrons in the lower valley and the upper valleys have the same temperature [22,23] and that the diffusion constant is independent of the electric field, the electron density, and spin. The time-dependent electron current is equal to the displacement current,

\[
J = env(E) - eD \frac{\partial n}{\partial x} = -\epsilon_s \frac{\partial E}{\partial t}.
\]

For a high-field domain propagating without a change of shape, in the domain’s reference frame

\[
ed E \frac{d n}{d E} = \frac{n[v(E) - v_{dom}] - n_0(v_K - v_{dom})}{n - n_0}
\]

The electron drift velocity outside of the domain, \( v_K = J/(en_0) \), and the electric field at such points is \( E_K \). The solution of Eq. (9) is

\[
n - \ln\left( \frac{n}{n_0} \right) - 1 = \frac{\epsilon_s}{en_0D} \int_{E_K}^{E} [v(E') - v_{dom}] dE'
\]

A self-consistent solution to Eq. (10) determines \( E(n) \). \( E(x') \) can then be found from Poisson’s equation,

\[
x' = x'_0 + \frac{e_s}{e} \int_{E_{dom}}^{E} \frac{dE}{n - n_0}
\]

where \( x'_0 \) is the location of the peak electric field in the domain’s frame. The local electron temperature \( T_e \) is

\[
k_B T_e = k_B T_1 + (2/3)e\tau_e \frac{E^2}{[1 + R \exp(-\Delta E/k_B T_e)]^{-1}}
\]

where \( T_i \) is the lattice temperature, \( \tau_e \sim 10^{-12} \) s the energy relaxation time, \( \Delta E \) the energy separation between the \( \Gamma \) and \( L \) valleys, and \( R \) the ratio of the density of states in the \( L \) to the \( \Gamma \) valleys (values from Ref. [21]). Figure 3 shows solutions of Eqs. (10) and (11) for \( n \) and \( E \) as a function of position for GaAs and InP for \( T_i = 300 \) K.

The spin amplification factor \( \gamma \) is shown in Figs. 3(e) and 3(f) for DP-phonon scattering, and in Figs. 3(g) and 3(h) for LO-phonon scattering. As \( T_e \) varies with position according to Eq. (12), \( \alpha \) must be evaluated as a function of \( T_e \) and \( n \) to determine \( \gamma \) properly. The electric field, and

FIG. 3 (color). Position dependence of the density \( n \) [(a) for GaAs, (b) for InP] and the electric field \( E \) [(c) for GaAs, (d) for InP] in the domain frame (\( x' = 0 \) is the domain center). Spin amplification rate \( \gamma \) for DP-phonon scattering [(e) for GaAs, (f) for InP] and for LO-phonon scattering [(g) for GaAs, (h) for InP]. The three curves correspond to different drift velocities far from the domain (different applied voltages to the Gunn diode): black is \( 5.7 \times 10^6 \) cm/s for GaAs, \( 2.6 \times 10^7 \) cm/s for InP; red is \( 5.0 \times 10^6 \) cm/s for GaAs, \( 2.45 \times 10^7 \) cm/s for InP; blue is \( 4.0 \times 10^6 \) cm/s for GaAs, \( 2.4 \times 10^7 \) cm/s for InP. Saturation spin polarization \( P_{sat} \) (corresponding to \( \gamma(P_{sat}) = T_1^{-1} \)) (i) for GaAs and (j) for InP.
thus \( \nabla \cdot \mathbf{j}_s \) is largest at the center of the domain. However, \( T_s \) is also greatest there, so the largest \( \gamma \) occurs near but not at \( x' = 0 \). For GaAs there is amplification for \( T_1 > 3 \) ps, and for InP for \( T_1 > 2 \) ps.

We propose Gunn diodes with \( n \sim 10^{18} \) cm\(^{-3} \) for the spin Gunn effect. For a lower doping density of \( 10^{16} \) cm\(^{-3} \) the \( T_1 \) of GaAs at 300 K is 50 ps [24] and our calculated \( \gamma \sim 4 \) ns\(^{-1} \), so spin amplification is not expected to occur. For \( n \sim 10^{18} \) cm\(^{-3} \) the \( T_s \) at peak \( \gamma(x') \) is 500 K, and the \( T^3 \) dependence of D'yakonov-Perel' precessional relaxation [24] suggests \( T_1 \sim 12 \) ps. Our calculated spin amplification rates of \( \gamma > 0.4 \) ps\(^{-1} \) are 5 times larger than this rapid spin relaxation rate, providing confidence that spin amplification will occur for room-temperature devices. At these high temperatures the enhanced electron-electron scattering [25] and the reduced mobility should also increase \( T_s \) far beyond 12 ps. Although higher densities than \( n \sim 10^{18} \) cm\(^{-3} \) produce even larger \( \gamma \)'s, the electric field may exceed breakdown.

The spin Gunn effect is a pulse of highly spin-polarized electrons located just before or just after a charge current pulse, depending on the dominant orbital scattering process. An estimate of the steady-state (saturation) values of the spin polarization \( (P_{\text{sat}}) \) requires an estimate of \( \alpha \) for \( P \neq 0 \). Multiplying the expression in Eq. (2) by \( 1 - P^2 \) yields the proper approximate behavior: amplification near \( P = 0 \) is unchanged, whereas amplification for \( P = \pm 1 \) vanishes. Shown in Figs. 3(i) and 3(j) are \( P_{\text{sat}} \) estimated for LO-phonon scattering determined by setting \( T_1 = 10 \) ps, using this modified form for \( \alpha(P) \), and solving \( \gamma(P_{\text{sat}}) = T_1^{-1} \). As \( \alpha(P = 1) = 0 \), \( \alpha \) changes 100% between \( P = 0 \) and \( P = 1 \). In contrast, \( n, \mu, \) and \( E \) change \( \sim 20\% \). Thus we neglect nonlinear effects on \( n, \mu, \) and \( E \) in our calculation of \( P_{\text{sat}} \). When \( \gamma(P = 0) = T_1^{-1}, P_{\text{sat}} = 0 \). The largest \( P_{\text{sat}} \) exceeds 80% for both GaAs and InP, and should be directly visible in a Faraday rotation measurement (e.g., Ref. [26]). When there is a convincing electrical method of spin-polarization detection in nonmagnetic semiconductors, these spin-polarized pulses will be detectable in that way.

We have demonstrated that, even when carrier scattering processes are entirely independent of spin, that the carrier mobility depends on the spin polarization of those carriers. This leads to a spin-dependent response of current flow to inhomogeneous electric fields and carrier densities. In the presence of a charge Gunn domain that spin-dependent response generates spin-polarization amplification and spontaneous spin-polarization generation. This spin Gunn effect is robust to temperature and spin relaxation, suggesting a wide range of potential applications and devices. Potential uses of the resulting series of highly spin-polarized pulses (each in register with a charge Gunn domain) include generating a reservoir of spin-polarized carriers within the semiconductor for spin-based logic, modulating the optical properties of semiconductor devices at high speed, and exploring resonant transport through quantum dots. Ultrafast optical excitation of carriers typically involves the repetitive generation of carriers every ~10 ns; our predicted electrically generated pulse trains of spin-polarized current may have similar uses in exploring the spin-dependent physics of various materials, including those with unfavorable optical properties such as silicon.

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