The Silicon Inversion Layer With A Ferromagnetic Gate: A Novel Spin Source

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Novel spin transport behavior is theoretically shown to result from replacing the usual metal (or poly-silicon) gate in a silicon field-effect transistor with a ferromagnet, separated from the semiconductor by an ultra-thin oxide. The spin-dependent interplay between the drift current (due to a source-drain bias) and the diffusion current (due to carrier leakage into the ferromagnetic gate) results in a rich variety of spin dependence in the current that flows through such a device. We examine two cases of particular interest: (1) creating a 100% spin-polarized electrical current and (2) creating a pure spin current without a net electrical current. A spin-valve consisting of two sequential ferromagnetic gates is shown to exhibit magnetoresistance dependent upon the relative orientations of the magnetization of the two ferromagnets. The magnetoresistance ratio grows to arbitrarily large values in the regime of low source-drain bias, and is limited only by the spin-flip time in the channel.

The creation, manipulation, and detection of spin-polarized carriers are the essential ingredients of semiconductor spintronics. Although well established using optical methods, the ultimate goal is to achieve this level of control over the spin degree of freedom in all-electrical devices. To this end, spin injection from ferromagnets into semiconductors and spin control through the Rashba spin-orbit effect have attracted much interest during the last few years. In addition, it has recently been proposed and experimentally verified that a pure spin current, without an accompanying electrical current, can be created in direct-gap semiconductors using the interference of one- and two-photon absorption processes. Such pure spin currents will allow for new probes of spin-dependent phenomena in semiconductors and may lead to alternate spintronics device designs not present in existing charge-based technology.

In this paper we present a method of creating fully spin-polarized charge currents and pure spin currents using a ferromagnetically-gated inversion layer in the regime of low source-drain bias. Our method is possible in any semiconductor, notably silicon, and not just those with well-defined optical transitions. It relies on a proximity effect in which semiconductor carriers acquire spin-dependent properties through coupling with a nearby ferromagnet. Experiments have shown that optically-pumped unipolarized electrons in a semiconductor acquire a net spin-polarization in the presence of an interface with a ferromagnet. The magnitude of the spin-dependent effects are optimized by confining the semiconductor carriers at the interface with the ferromagnet, with the ferromagnet acting as the electrically-biased gate responsible for the inversion. The crucial parameter is the thickness of the oxide barrier which separates the semiconductor from the ferromagnet; since the coupling of the two depends exponentially on their separation, our proposal will be most relevant for ultrathin gate oxides at the forefront of current technology. The balance of growing oxides thin enough to produce ample coupling while preserving the functionality of the inversion layer is delicate, although we point out that we are merely taking advantage of the aggressive scaling of field-effect transistors to the nanoscale. In addition, we will discuss the behavior of a recently-proposed spin-valve with two sequential ferromagnetic gates in the same regime of low source-drain bias, where the magnetoresistance ratio due to the relative orientation of the ferromagnet magnetizations can grow to arbitrarily large values.

To demonstrate the operational principle of the device, consider the spin-dependent current in a two-dimensional electron gas (2DEG). We will concentrate on the silicon inversion layer with an SiO₂ barrier and a ferromagnetic gate, and consider only a single occupied subband in the silicon. For simplicity, we will assume the two spin channels are completely decoupled, but we will return to address any coupling between the two spin channels later in the paper. The device is shown in Fig. 1(a): the growth axis is in the z-direction, the in-plane current flows in the x-direction, and we assume the device is translationally invariant in the y-direction. The in-plane electrical current $J_\sigma(x)$ in spin channel $\sigma = \{\uparrow, \downarrow\}$ contains both drift and diffusion terms,

$$J_\sigma(x) = g_\sigma(x)E_x + eD_\sigma(x)\frac{\partial}{\partial x}N_\sigma(x) ,$$

where $-e$ is the electron charge, $g_\sigma(x)$ is the Drude conductivity, $E_x$ is the electric field that drives the in-plane current, $D_\sigma(x)$ is the diffusion constant, and $N_\sigma(x)$ is spatially-dependent 2DEG density. To achieve spin-dependent transport, either the transport coefficients or the 2DEG density must vary considerably between the two spin channels. We show below how the coupling between the 2DEG and a ferromagnetic gate achieves this splitting.

In Ref. the coupling was calculated from the wavefunction matching conditions, resulting in an equation which specified the spin-dependent complex energy of the confined inversion layer state coupled to the ferromagnet. In Ref. an effective tight-binding Hamiltonian was derived from the effective-mass Hamiltonian of
the silicon/SiO$_2$/ferromagnet interface. The form of this Hamiltonian allowed for the calculation of the 2DEG self-energy due to the interaction with the ferromagnet, the approach we will adopt in this paper. The results of the derivation in Ref. 21 are summarized below in order to clarify the method of calculation used throughout the rest of this paper. The effective Hamiltonian of the 2DEG coupled to the ferromagnetic gate is

$$H = \sum_\sigma \epsilon_\sigma^b a_\sigma^b + \sum_{k,\sigma} \epsilon_{k,\sigma}^k c_{k,\sigma}^k + \sum_{k,\sigma} \left[ a_\sigma^i V_{k,\sigma}^\mathrm{fm} c_{k,\sigma} + c_{k,\sigma}^i \left( V_{k,\sigma}^\mathrm{fm} \right)^* a_\sigma \right].$$  

(2)

A one-dimensional calculation is possible for the coupling calculation because the conservation of the in-plane wavevector is relaxed. The operator $a_\sigma^i$ creates a ferromagnet state with spin $\sigma$, energy $\epsilon^i_\sigma$, and wavefunction $\chi^i_\sigma(z)$, which is the lowest bound state of the potential

$$V^\mathrm{si}(z) = \left[ -\bar{U}_b - eE^\mathrm{si}_z \cdot (z - z_b) \right] \Theta(z - z_b),$$  

(3)

where $\bar{U}_b$ is the oxide barrier height from the bottom of the semiconductor potential, $E^\mathrm{si}_z$ is the electric field in the semiconductor, and $z_b$ is the thickness of the oxide barrier. The "0" of energy has been put at the top right side of the barrier to simplify the calculations. The operator $\epsilon_{k,\sigma}^k$ creates a ferromagnet state with spin $\sigma$, wavevector $k$, energy $\epsilon_{k,\sigma}^k$, and wavefunction $\phi_{k,\sigma}^k(z)$, which are states of the potential

$$V_{\sigma}^{\mathrm{fm}}(z) = -\left[ U_{\mathrm{fm}} + \frac{\Delta}{2} \mathbf{\hat{\sigma}} \cdot \mathbf{M} \right] \Theta(-z)$$

$$-eE^b_z \cdot (z - z_b) \Theta(z) \Theta(z_b - z),$$  

(4)

where $U_{\mathrm{fm}} + \Delta/2$ is the Fermi energy of the majority spin band in the ferromagnet, $U_{\mathrm{fm}} - \Delta/2$ is the Fermi energy of the minority spin band in the ferromagnet, and $E^b_z$ is the electric field in the barrier. Note that for simplicity we treat the ferromagnet as exchange-split parabolic bands. The coupling between the 2DEG and the ferromagnet is approximated by

$$V_{k,\sigma}^{\mathrm{fm}} = \int dz \left[ \phi_{k,\sigma}^m(z) \right]^* V_{\sigma}^{\mathrm{fm}}(z) \chi^i_\sigma(z),$$  

(5)

which is basically an overlap integral with an exponentially decaying term. Eq. (4) is an approximation of the effective-mass Hamiltonian of the Si/SiO$_2$/ferromagnet interface in which only the most significant terms in the coupling have been retained.

From the simple tight-binding Hamiltonian, Eq. (2), the self-energy of the 2DEG electrons due to the interaction with the ferromagnetic gate is

$$\Sigma_\sigma(E) = \sum_k \frac{|V_{k,\sigma}^{\mathrm{fm}}|^2}{E - \epsilon_{k,\sigma}^f + i \gamma_{k,\sigma}^{\mathrm{fm}}}.$$  

(6)

To account for strong scattering in the ferromagnet, a large imaginary part has been added to the ferromagnet states ($\gamma_{k,\sigma}^{\mathrm{fm}}$). Calculating the complex energy $\bar{E}$ which satisfies $\bar{E} - \epsilon^i_\sigma + i0^+ - \Sigma_\sigma(\bar{E}) = 0$, we can evaluate both the spin-dependent 2DEG level shift, $\Delta_\uparrow(\bar{E}) = \Re \left[ \Sigma_\uparrow(\bar{E}) \right]$, and the spin-dependent 2DEG lifetime, $\tau_\sigma(\bar{E}) = -\hbar/2\text{Im} \left[ \Sigma_\sigma(\bar{E}) \right]$, due to the coupling with the ferromagnet. The spin-splitting due to the level shift, $|\Delta_\uparrow - \Delta_\downarrow|$, is very small compared to the Fermi energy of the 2DEG for even the thinnest practical oxides, and will be neglected. On the other hand, the spin-dependent lifetime, which represents the time for an inversion layer electron to irreversibly "fall" into the ferromagnet, is in the picosecond range for oxide thicknesses below 10 Å, which approaches the intrinsic scattering time of the silicon inversion layer, $\tau_0 \approx 1$ ps. The ratio of the lifetimes for the two spin channels $\tau_\uparrow/\tau_\downarrow$ is roughly a factor of 2 for all oxide thicknesses; spin-dependent transport results, which can be harnessed for spintronics purposes. Using the following parameters for the Si/SiO$_2$/Fe interface, we calculate the scattering times to be $\tau_\uparrow = 3$ ps and $\tau_\downarrow = 6$ ps. For silicon, the longi-
tudinal effective mass responsible for the confinement is \(m^*_{x,1} = 0.91 m_0\), the transverse effective mass responsible for 2DEG transport is \(m^*_{x,2} = 0.19 m_0\), the dielectric constant is \(\epsilon_{d} = 11.7\), and the equilibrium density of the 2DEG is assumed to be \(N_0 = 10^{12} \text{ cm}^{-2}\). For silicon dioxide the effective mass is \(m^*_b = 0.3 m_0\), the dielectric constant is \(\epsilon_b = 3.9\), and the barrier height (from the Fermi level) is \(U_b = 3.2 \text{ eV}\). For the ferromagnet, we use \(U_{m} = 2.65 \text{ eV}\), exchange splitting \(\Delta = 3.9 \text{ eV}\), effective mass \(m^*_{\text{FM}} = m_0^{2/3}\) and, for simplicity, a wavevector-independent imaginary part of the ferromagnetic energy \(\gamma_{\text{FM}}^{\text{im}} = 1.1 \text{ eV}\) and \(\gamma_{\text{FM}}^{\text{im}} = 0.8 \text{ eV}^{2/3}\). The electric field in the barrier is assumed to be \(E_b^0 = -10 \text{ MeV/cm}\).

Having calculated the \(z\)-axis properties of the ferromagnetically-gated silicon field-effect transistor, we now examine the 2DEG transport in the \(\hat{x}\)-direction. Due to the electrical bias on the ferromagnet, the 2DEG current is not constant under the gate and will leak at a rate of

\[
\frac{d}{dx} J_{\sigma} = -e \left[ \frac{-N_{\sigma}(x)}{\tau_{\sigma}} \right].
\]

Note that because the flow of electrons is opposite to the current, electrons leaking out of the 2DEG into the ferromagnetic gate implies that a positive current flows into the 2DEG; the current will increase under the gate. Combined with Eq. 1 and the appropriate boundary conditions (the 2DEG has its equilibrium density at the source and drain, \(N_\sigma(x_s) = N_\sigma(x_d) = N_0/2\), this results in a differential equation for the spatially-dependent, spin-dependent 2DEG density. The new scattering channel due to the interaction with the ferromagnet must also be included in the Drude conductivity,

\[
g_{\sigma}(x) = \frac{N_{\sigma}(x) e^2}{m^*_{x,\text{FM}}} \left( \frac{1}{\tau_0} + \frac{1}{\tau_{\sigma}} \right)^{-1}.
\]

The diffusion constant in two dimensions calculated using the above conductivity is

\[
D_{\sigma}(x) = \frac{2 \hbar^2 c_{F,\sigma}^2(x)}{m^*_{x,\text{FM}} \left( \frac{1}{\tau_0} + \frac{1}{\tau_{\sigma}} \right) \left( 1 - e^{-c_{F,\sigma}^2(x)/k_B T} \right)},
\]

where the spin-dependent Fermi level is \(c_{F,\sigma}^2(x) = 2 \pi \hbar^2 N_{\sigma}(x)/m^*_{x,\text{FM}}\). In the following we assume the gate length in the \(\hat{x}\)-direction is approximately 1000 Å, so that the source is at \(x_s = 0\) and the drain is at \(x_d = 1000 \text{ Å}\), and we assume that the gate extends 1 μm in the \(\hat{y}\)-direction. For concreteness, we will assume throughout this paper that the in-plane electric field is negative, \(E_x < 0\), such that, in the absence of leakage, a negative current would flow through the 2DEG (electrons flow from the source to the drain). In addition, we assume the confinement is homogeneous along the channel, so that \(\tau_0\) and \(\tau_{\sigma}\) are constant.

In a silicon field-effect transistor with a thick gate oxide there is no leakage of 2DEG electrons because the wavefunction cannot penetrate into the gate. Neglecting the spin dependence for the time being, we examine the behavior of a silicon field-effect transistor with an ultra-thin gate oxide. Finite penetration of the 2DEG wavefunction through the oxide and into the gate causes a tunnel current to flow. The Fermi level in the gate is lower than the Fermi level in the inversion layer due to the gate bias; electrons that tunnel into the gate will inelastically fall to the gate Fermi level and have no way to return to the 2DEG, decreasing the density in the 2DEG.

As the in-plane field is made more negative the drain current will increase under the gate. Combined with Eq. 1 and the appropriate boundary conditions (the 2DEG has its equilibrium density at the source and drain, \(N_\sigma(x_s) = N_\sigma(x_d) = N_0/2\), this results in a differential equation for the spatially-dependent, spin-dependent 2DEG density. The new scattering channel due to the interaction with the ferromagnet must also be included in the Drude conductivity,

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With a ferromagnetic gate, the above analysis still holds for each spin channel separately (provided that the spin-flip time is much longer than the transit time through the device). The lifetime for 2DEG electrons to fall into the gate is spin-dependent due to the spin-dependent coupling in the Hamiltonian, Eq. (2). Importantly, the diffusive currents for spin \(\uparrow\) electrons and

**FIG. 2:** (Top) A plot of the spin-dependent drain currents \(J_{\uparrow}(x_d)\) (full line) and \(J_{\downarrow}(x_d)\) (dashed line) as a function of the in-plane field \(E_x\). (Bottom) A plot of the total drain current \(J_{\uparrow}(x_d) + J_{\downarrow}(x_d)\) (full line) and the spin current \(J_{\uparrow}(x_d) - J_{\downarrow}(x_d)\) (dashed line) as a function of \(E_x\).
spin $\downarrow$ electrons must also be different at zero source-drain bias, and hence the in-plane field required to exactly cancel the diffusive backflow at the drain contact will be different in the two spin channels.

The spin-dependent drain currents $J_\uparrow(x_d)$ and $J_\downarrow(x_d)$ are plotted as functions of the in-plane field $|E_x|$ in the top panel of Fig. 2. The total current $J_\uparrow(x_d) + J_\downarrow(x_d)$ and the spin current $J_\uparrow(x_d) - J_\downarrow(x_d)$ are plotted as functions of $|E_x|$ in the bottom panel of Fig. 2. At very low source-drain bias the drain currents are positive in both spin channels, but have different magnitudes due to the different leakage rates for the two spin channels; because $\tau_\uparrow < \tau_\downarrow$, more spin $\uparrow$ electrons than $\downarrow$ electrons. The larger gradient in the density in the spin $\uparrow$ channel results in $J_\uparrow(x_d) > J_\downarrow(x_d)$. At the in-plane field marked A, the drain current in the $\downarrow$ spin channel is $J_\downarrow(x_d) = 0$; the diffusive current is exactly cancelled by the drift current. The larger diffusive current in the spin $\uparrow$ channel is still of higher magnitude than the drift current. Spin $\uparrow$ electrons will flow into the 2DEG at the drain contact, resulting in a 100% spin-polarized current. At the in-plane field marked B in Fig. 2 the drain currents in the two spin channels are equal and opposite, $J_\uparrow(x_d) = -J_\downarrow(x_d)$. No net charge current flows through the drain, but a pure spin current flows such that spin $\uparrow$ electrons are transferred into the 2DEG and spin $\downarrow$ electrons are transferred out of the 2DEG at the drain, i.e., the silicon inversion layer acts as a spin pump at the field marked B. At the field marked C the drain current in the spin $\downarrow$ channel is negative, while in the spin $\uparrow$ channel the drift and diffusive currents exactly cancel, $J_\uparrow(x_d) = 0$. Spin $\downarrow$ electrons will flow out of the the 2DEG, resulting in a 100% spin-polarized drain current. As the magnitude of the in-plane field is increased further the electrical currents in both spin channels are negative; the spin $\downarrow$ channel carries more current because its conductivity is higher than that of the spin $\uparrow$ channel. Electrons flow out of the 2DEG drain with some polarization. Note that the roles of the spin channels can be exchanged by reversing the gate magnetization, such that the drain contact of this ferromagnetically-gated silicon inversion layer can be used as a source for both fully spin-polarized charge currents and pure spin currents with either spin $\uparrow$ or $\downarrow$. For positive in-plane electric fields $E_x > 0$, the same phenomena happen at the source contact.

The behavior of the spin-dependent currents throughout the 2DEG are plotted in Fig. 3 near the in-plane fields A (top panel), B (middle panel), and C (bottom panel). The leakage of electrons under the gate is evident, as the current is not constant and increases under the gate. The plots show that in this region of source-drain bias the drift current is just beginning to overtake the diffusion current at the drain contact (the drift and diffusion currents flow in the same direction at the source contact).

The spin effects present in the silicon inversion layer with a single ferromagnetic gate could be very attractive for spintronics applications. We will now describe a simple all-electrical measurement to take advantage of the spin-dependent 2DEG transport. Recently we proposed a planar semiconductor spin-valve which relies upon the coupling of the inversion layer electrons to sequential ferromagnets. The space between the ferromagnets is filled with a paramagnetic metal to ensure homogeneous 2DEG confinement throughout the device. A diagram of the device is shown in Fig. 1(b). The two ferromagnets are patterned with different aspect ratios, such that the magnetization of one ferromagnet can be reversed by an external field without affect the magnetization of the other ferromagnet.

Assuming the two spin channels are decoupled throughout the device, let us examine the total 2DEG current at the drain contact for parallel ferromagnet magnetizations, $J_p(x_d)$. One spin channel will see the spin $\uparrow$ scattering time $\tau_\uparrow$ under both ferromagnets, and the other spin channel will see the spin $\downarrow$ scattering time $\tau_\downarrow$ under both ferromagnets; the total current $J_p(x_d)$ will be the sum of the currents in the two spin channels. Switching the magnetization of the second ferromagnet, one spin channel will see the spin $\uparrow$ scattering time $\tau_\uparrow$ under the first ferromagnet and the spin $\downarrow$ scattering time $\tau_\downarrow$ under the second ferromagnet, while the other spin channel will see the reverse. Because the density and current must be continuous in both spin channels, the total drain current for antiparallel magnetizations $J_{ap}(x_d)$ will in general be different from $J_p(x_d)$. The net result is a magnetoresistance effect, in which the 2DEG current is dependent upon the relative orientation of the ferromagnet magnetizations. We define the magnetoresistance ratio as

$$MR = 100 \cdot \frac{|J_p(x_d) - J_{ap}(x_d)|}{J_p(x_d)}.$$  \hspace{1cm} (10)$$

This quantity is plotted as the full line in Fig. 4 as a function of the in-plane electric field $|E_x|$, for an infi-
For ferromagnetic gates, for different values of the spin-flip time $\tau_{sf}$. Both ferromagnets are assumed to be 1000 Å long in the $\hat{x}$-direction, with a 200 Å gap between them. The magnetoresistance ratio grows to values greater than 100% when $J_\sigma(x_d) \to 0$, at which point a pure spin current would flow in the parallel configuration.

The spin-flip time $\tau_{sf}$ couples the two spin channels together, driving them to the same density. Short spin-flip times ($\tau_{sf}$ comparable to the scattering times $\tau_0$ and $\tau_\sigma$) will wash out any spin-dependent transport effects. For coupled spin channels, Eq. 7 must be replaced with

$$\frac{d}{dx} J_\sigma = -e \left[ \frac{N_\sigma(x)}{\tau_\sigma} - \frac{N_\sigma(x) - N_\sigma(x)}{\tau_{sf}} \right], \quad (11)$$

where $\bar{\sigma}$ is spin opposite to $\sigma$. The magnetoresistance ratio is plotted for two values of the spin-flip time near the intrinsic scattering time, $\tau_{sf} = 1.0$ ps (dashed line) and $\tau_{sf} = 0.1$ ps (dotted line) in Fig. 4. Short spin-flip times drastically reduce the $MR$; the currents in the two spin channels are so strongly coupled that the total current through the 2DEG is only slightly altered when switching from parallel to antiparallel magnetizations. Although short spin relaxation times should not be a problem in silicon, it could be an issue in other semiconductors.

In conclusion, we have shown how the unavoidable issue of 2DEG carrier leakage in silicon field-effect transistors with ultra-thin gate oxides can be put to good use for spintronics applications. By replacing the metal gate with a ferromagnet, the coupling between the silicon inversion layer and the gate becomes spin-dependent, resulting in spin-dependent 2DEG transport. In the low source-drain bias regime, the drift current (first term on right side of Eq. 11) and the diffusion current (second term on right side of Eq. 11) are of the same order; the spin-dependent interplay between the two results in a variety of spin currents that flow through the contacts to such a device. We have shown how the ferromagnetically-gated silicon inversion layer can produce both fully spin-polarized charge currents and pure spin currents, without any net charge transfer. In addition, we have shown that if the gate is made up of two sequential ferromagnets, a magnetoresistance effect occurs in the 2DEG current dependent upon the relative orientation of the two ferromagnet magnetizations. The magnetoresistance ratio can exceed 100% in this low source-drain bias regime.

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