Experimental Spin Ratchet

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Spintronics relies on the ability to transport and use the spin properties of an electron rather than its charge. We describe a spin ratchet at the single-electron level that produces spin currents with no net bias or charge transport. Our device is based on the ground-state energetics of a single-electron transistor comprising a superconducting island connected to normal leads via tunnel barriers with different resistances that break spatial symmetry. We demonstrate spin transport and quantify the spin ratchet efficiency by using ferromagnetic leads with known spin polarization. Our results are modeled theoretically and provide a robust route to the generation and manipulation of pure spin currents.

Brownian motors or ratchets refer to directed transport in the presence of a signal or perturbation that drives the system without an obvious bias in any preferred direction of motion. The perturbation generates useful work, for instance, the transport of particles, when combined with asymmetry, often realized by a so-called ratchet potential (Fig. 1A) (1–3). Experimental realizations of ratchets are spread over many different fields of biology, chemistry, and physics, where the perturbation may be external to the system (e.g., induced by an experimentalist) or intrinsic to it (e.g., nonthermal noise). In mesoscopic structures, experiments have demonstrated ratchets in both the quantum and classical limits (4–6). On such small scales, noise rectification with ratchets can be used to control particle transport and has become one of the most promising techniques for powering nanodevices (3).

Because of the growing interest in the spin degree of freedom as a carrier of information (7) as well as a means to address fundamental properties of quantum mechanics and quantum computation (8), a variety of ratchets have been proposed in pursuit of unidirectional spin currents and spin control (9–12). A pure spin ratchet (11) generalizes the particle ratchet mechanism (1–3), enabling pure spin currents by means of broken spatial symmetry (9–12). Thus, an indispensable hallmark for a spin ratchet is the breaking of the inversion symmetry for spin but not charge (11), whereby the ratchet-potential easy direction for one spin orientation is opposite to the ratchet-potential easy direction for the other spin orientation (Fig. 1A). Recent theoretical efforts use mesoscopic semiconductors and nonuniform magnetic fields (9), asymmetric periodic structures with Rashba spin-orbit interaction (10), and double-well structures combined with local external magnetic fields and resonant tunneling (12).

The concept of our spin ratchet is different from what has been proposed before. A small-volume superconducting (S) island is connected via tunnel junctions with two normal metal electrodes [N(l) and N(r)] to form an asymmetric single-electron transistor (SET) with different tunneling resistances (Fig. 1B). A voltage $V$ applied across the SET drives the system, whereas a voltage on the back gate $V_g$ sets the induced gate charge $Q = nC_gV_g$ on the island, with $C_g$ the capacitive coupling between the island and the gate.

At low temperatures, parity effects in the superconducting island are important (13–16). When the number of conduction electrons $n$ is odd, there is necessarily one unpaired electron that is manifest as a quasiparticle excitation (13, 17). The ground state energy of the system for odd $n$ is higher than for even $n$ by the superconducting gap $\Delta$, which in our design is larger than the charging energy, $E_c$ (Fig. 1C). In order to break the symmetry between spin-up and spin-down transport, a magnetic field $B$ is applied in-plane along the axis of the electrodes [spin up refers to spins parallel to $B$, whereas spin down refers to spins antiparallel to $B$]. This field splits the quasiparticle levels (e.g., $n = 1$ and $n = 0$) by the Zeeman energy $E_z = g_n\mu_B B$, where $g$ is the $g$ factor of the superconductor and $\mu_B$ the Bohr magneton, but it does not affect the Cooper-pair states (e.g., $n = 0$ and $n = 2$), which are singlet states, and it weakly reduces $\Delta$ because orbital deparing is minimized by an in-plane $B$ (18) (Fig. 1, D and E). The $n = 1$ state shifts down continuously with increasing $B$ and, at $B_{SR} = (\Delta - E_c)/(g\mu_B)$...
Insight into the underlying mechanism can be gained by analyzing the relevant charge transport processes and their occurrence rates. Single-electron Andreev processes cause transitions between even and quasi-particle states whereas two-electron Andreev and quasi-particle thresholds become negative at positive $B$, and one of the above-gap spin-down electrons through the SET. A cycle that only uses transitions between $n=2$ and $n=0$ can transport spin current into one preferred direction in the following manner. A cycle that only uses transitions between $n=0$ and $n=2$ can transport spin current in the opposite direction.

We have fabricated a SET spin ratchet that only uses transitions between $n=2$ and $n=0$ and that is driven by a magnetic field. The spin ratchet is effective for an unbiased SET, whereas the spin orientation of moving electrons is reversed with a magnetic field. The spin ratchet effect occurs at $B=B_0$, the ground state is reached ($G=0$) and the one ($n=2$) excess Cooper-pair state is reached ($G=1$). For a spin ratchet, the rate hierarchy are shown schematically in Fig. 1, and the thresholds for single- and two-electron processes become distinct in the junctions ($l$ and $r$) when $B=B_0$. When a voltage $V$ with zero mean is applied, the spin current is reversed, whereas a spin current in the opposite direction is observed when $V$ is applied. The spin ratchet mechanism in Fig. 1 is based on the spin dependence of the leads from two different angles of deposition of the leads from two different angles.

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leads, $P_F$, measures the relative contribution of cycles 01 and 21. For a quantitative measurement of the spin-ratchet efficiency, we independently determined $P_F$. We accomplished this by using similarly fabricated junctions embedded in non-local spin devices, for which we obtained $P_F \sim 0.28$ (20, 21).

The electron transport properties of such an FSF SET were fully characterized by means of differential conductance $dI/dV$ measurements at above-gap voltage bias, from which we estimated $\Gamma_0^+ \approx 8 \times 10^6 \text{ s}^{-1} < \Gamma_0^- \approx 4 \times 10^7 \text{ s}^{-1} < \Gamma_{l,r}^+ \approx 5 \times 10^8 \text{ s}^{-1}$ (19). Figure 2 shows the evolution of $dI/dV$ as a function of the magnetic field at below-gap bias for this device. At $B = 0$, we observe a symmetric response about $V = 0$ (Fig. 2A). There, $dI/dV$ is zero within the sensitivity of our measurements for voltage magnitudes below the gap, except at the quasi-particle thresholds, where it presents a peak whose intensity is nearly independent of $V$ and $P_F$ (22). The below-gap quasi-particle thresholds cross at about $V_0 = 259 \mu\text{V}$ (Fig. 2A). This is in agreement with $V_0 \sim 2(\Delta - E_g)/e$ (Fig. 1C) when using $E_g = 170 \mu\text{V}$ and $\Delta \approx 303 \mu\text{V}$ as obtained from the above-gap thresholds [Fig. S2 (19)]. At $B = 1 \text{T}$, $V_0$ decreases to $94 \mu\text{V}$ because of $E_Z$. At $B = 1.5 \text{T}$, $V_0$ becomes zero and the SET is in the pure spin ratchet regime (Fig. 1D) (23).

Of key importance, the differential conductance at $B \neq 0$ (Fig. 2, B and C) is no longer symmetric about $V = 0$, presenting a larger magnitude for $V > 0$ than for $V < 0$ along the below-gap quasi-particle thresholds. This observation is consistent with the description in Fig. 1 and represents an experimental confirmation of the spin ratchet effect. Indeed, the asymmetry results from $P_F$ and the fact that the current across the SET for positive and negative $V$ has opposite spin polarization. The leads are always magnetized parallel to each other along the $B$ direction and, because $P_F > 0$, they favor the dominant spin-down current cycle 01 at $V > 0$ and hinder the dominant spin-up current cycle 21 at $V < 0$. We quantify such a transport asymmetry by using the parameter $\beta = (G^+_p - G^-_p)/(G^+_p + G^-_p)$, where $G^+_p = dI/dV |_{\text{peak}} (V > 0)$ and $G^-_p = dI/dV |_{\text{peak}} (V < 0)$ are the values of the peak conductances along the dotted white lines in Fig. 2. At $B = 0$ (Figs. 2A and 3A), $\beta$ is zero within the sensitivity of our measurements, as expected. At $B = 1 \text{T}$ and $B = 1.5 \text{T}$ (Fig. 2, B and C, and Fig. 3, B and C), the difference between $G^+_p$ and $G^-_p$ becomes apparent, resulting in $\beta \sim 0.14$ in both cases.

We define the spin-ratchet efficiency $\eta_{\text{SET}}$ as equal to the spin-filtering capability $\eta_{\text{SET}} \approx (1 - \alpha)/(1 + \alpha)$ of our device, where the ratio $\alpha = (1 - \Gamma^-_0)/\Gamma_0^+ \approx R_L/R_t$ measures the asymmetry of the SET and $R_0$ are the associated normal tunnel resistance of junctions 1 and 3 (Fig. 1B). For $\alpha = 0$, nearly perfect filtering, that is, $\eta_{\text{SET}} \approx 1$, is achieved. In such a scenario, $\beta$ directly measures the effective polarization of the leads; that is, $\beta = P_F \approx 0.28$. For $\alpha > 0$, a decrease in filtering efficiency is expected, and therefore $\beta$ should decrease accordingly as $\beta \approx \eta_{\text{SET}} P_F$. For our device, $R_L \approx 350 \text{ k}\Omega$ and $R_t \approx 70 \text{ k}\Omega$ and $\alpha \approx 0.2$. We thus estimate $\eta_{\text{SET}} \approx 0.67$ and $\beta \approx \eta_{\text{SET}} P_F \approx 0.19$, a value that is somewhat larger than that obtained with our measurements ($\beta \approx 0.14$), which results in $\eta_{\text{SET}} \approx 0.5$. This discrepancy could be related to the uncertainty in the estimation of $R_L$ or to Andreev reflections in one of the junctions, which could contribute an unpolarized component to the total current.

At magnetic fields $B > B_{SR}$, where the spin-up and spin-down quasi-particle thresholds are resolved, the SET behaves as a diode that filters spin-up or spin-down quasi-particles (Figs. 2D and 3D). Namely, the current should be polarized...
Spin Transfer Torques in MnSi at Ultralow Current Densities

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Spin manipulation using electric currents is one of the most promising directions in the field of spintronics. We used neutron scattering to observe the influence of an electric current on the magnetic structure in a bulk material. In the skyrmion lattice of manganese silicon, where the spins form a lattice of magnetic vortices similar to the vortex lattice in type II superconductors, we observe the rotation of the diffraction pattern in response to currents that are over five orders of magnitude smaller than those typically applied in experimental studies on current-driven magnetization dynamics in nanostructures. We attribute our observations to an extremely efficient coupling of inhomogeneous spin currents to topologically stable knots in spin structures.

The discovery of the effect of giant magnetoresistance, now used commercially in the hard disk drive industry, is widely recognized as the starting point of the field of spintronics. It represents the first example of electric currents controlled efficiently by spin structures. The complementary process of so-called spin transfer torques, where magnetic structures and textures are manipulated by electric currents, appears to be even more promising. For instance, strong current pulses allow the movement of ferromagnetic domain walls (3, 4), the switching of magnetic domains in multilayer devices (5, 6), the induction of microwave oscillations in nanomagnets (7), and the switching of ferromagnetic semiconductor structures (8). However, the typical current densities required to create observable spin transfer torques in present-day studies exceed 10¹⁴ A m⁻². Because this implies extreme ohmic heating, it was generally believed that spin torque effects can be studied exclusively in nanostructures. We report the observation of spin transfer torques in a bulk material, the skyrmion lattice phase of MnSi. The spin transfer torques appear when the current density exceeds an ultralow threshold of ~10⁻⁵ A m⁻², five orders of magnitude smaller than those used typically in experimental studies on current-driven magnetization dynamics in ferromagnetic metals and semiconductors.

The skyrmion lattice in chiral magnets, like MnSi and related B20 compounds, was only recently discovered in neutron-scattering studies (9–12) and confirmed to exist in Lorentz force microscopy for Fe₆₅-Co₃₀-Si₁₅ (x = 0.5) (13). It represents a new form of magnetic order that may be viewed as a crystallization of topologically stable knots of the spin structure that shares remarkable similarities with the mixed state in type II superconductors. For zero magnetic field (Fig. 1A), helimagnetic order appears in MnSi below the critical temperature Tc = 29.5 K.