Spin-torque transistor

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A magnetoelectronic thin-film transistor is proposed that can display negative differential resistance and gain. The working principle is the modulation of the soure–drain current in a spin valve by the magnetization of a third electrode, which is rotated by the spin-torque created by a control spin valve. The device can operate at room temperature, but in order to be useful, ferromagnetic materials with polarizations close to unity are required. © *2003 American Institute of Physics.*
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Magnetoelectronic circuits differ from conventional ones by the use of ferromagnetic metals. Electric currents depend on the relative orientation of the magnetization vector of different magnetic elements, giving rise to the giant magnetoresistance. The additional functionalities are useful for sensing and data storage applications, like magnetic random access memories (MRAMs).[1] Several ideas on how to employ the spin degree of freedom for other applications exist.[2,3]

Here, we pursue the "spin–flip transistor", a three-terminal device consisting of an antiparallel spin valve in which the conducting channel is in contact with a ferromagnetic base.[4] The source–drain current is modulated by the base magnetization direction, since the latter affects the spin accumulation in the conducting channel. It has been predicted[5,6] and measured[7] that the magnetization in spin valves can be switched by an electric current. In Ref. 8, it was suggested to use the spin–flip transistor as an MRAM element, in which the base magnetization is switched by the spin torque due to the induced spin accumulation. In the following, we investigate the device parameters of the spin–flip transistor operated as an amplifier by controlling the base magnetization by a second spin valve in an integrated device that we call "spin-torque transistor" (Fig. 1). The lower part of this device consists of source and drain contacts made from high-coercivity metallic magnets with antiparallel magnetizations that are biased by an electrochemical potential μ_S. The source–drain electric current I_{SD} induces a spin accumulation in the normal metal node $N1$. A spin-flip transistor is made by attaching an electrically floating base (or gate) electrode B, which is magnetically very soft and has good electric contact to $N1$. When the magnetization angle θ is not 0 or π a spin current flows into the base that decreases the spin accumulation and increases I_{SD} with θ up to $\pi/2$. On the other hand, the spin accumulation in $N1$ exerts a torque on B which strives to lower θ. θ, and thus I_{SD}, could be modulated, e.g., by the Ørsted magnetic field generated electrically by the "write line" of an MRAM element, but this does not appear viable. We, therefore, propose the transistor in Fig. 1 which integrates a second spin valve with magnetizations rotated by $\pi/2$ from the lower one. An applied bias μ_B creates another torque which pulls the magnetization into the direction collinear to the upper contacts. The base electrode then settles into a configuration at which both torques cancel each other. A variation in μ_B then modulates θ and consequently I_{SD}. In the following, we discuss the figures of merit of the transistor action, viz. the transconductance and the current gain of this device.

For most transition-metal-based structures, exchange splittings are large, Fermi wavelengths are short, and interfaces are disordered. Electron propagation is, therefore, diffuse and ferromagnetic (transverse spin) coherence lengths are smaller than the mean-free path.[9] In these limits, the magnetoelectronic circuit theory is a convenient formalism.[4,10] Spin–flip relaxation can be disregarded in the normal metal node of small enough structures, since e.g., Al

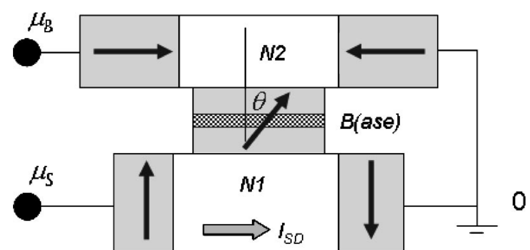

FIG. 1. Schematic sketch of the spin-torque transistor consisting of two spin-flip transistors with a common base contact B and source–drain contact magnetizations which are rotated by 90° relative to each other. The magnetization direction of the base B is controlled by the chemical potentials μ_B and μ_S.

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and Cu have spin–flip diffusion lengths of the order of a micron.[3] Spin flip in the source and drain electrodes can simply be included by taking their magnetically active thickness as the smaller of the spin–flip diffusion length and physical thickness. The base electrode is assumed to be magnetically soft and the thickness is taken to be smaller than the spin–flip diffusion length. These assumptions are not necessary, since magnetic anisotropies and spin flip in the base can readily be taken into account, but these complications only reduce the device performance and will be treated elsewhere. The source–drain current dependence on the base magnetization angle θ then reads:[4]

$$I_{SD}(\theta)=\frac{e}{h}\;\frac{g_S\mu_S}{2}\;\frac{2(g_B^{\uparrow\downarrow}+g_S(1-p_S^2))g_S^{\uparrow\downarrow}+g_B^{\uparrow\downarrow}(-2g_S^{\uparrow\downarrow}+g_S(1-p_S^2))\cos^2\theta}{2(g_S+g_B^{\uparrow\downarrow})g_S^{\uparrow\downarrow}+g_B^{\uparrow\downarrow}(g_S-2g_S^{\uparrow\downarrow})\cos^2\theta}, \tag{1}$$

where $g_S=g_S^{\uparrow}+g_S^{\downarrow}$ and $p_S=(g_S^{\uparrow}-g_S^{\downarrow})/g_S$ are the normal conductance and polarization of the source, and $g_S^{\uparrow\downarrow}$ and $g_B^{\uparrow\downarrow}$ are the "mixing conductances" of the source and base contacts, respectively. Drain and source contact conductances are taken to be identical and the normal conductance of the base is assumed to vanish. All conductance parameters are in units of the conductance quantum e^2/h, contain bulk and interface contributions,[10] can be computed from first-principles and are taken to be real.[8] The torque on the base magnetization created by the spin accumulation is proportional to the transverse spin current[10] into B:

$$L_B(\theta)=\frac{1}{2}\,\frac{p_S g_S g_S^{\uparrow\downarrow}g_B^{\uparrow\downarrow}\sin\theta\mu_S}{2(g_S+g_B^{\uparrow\downarrow})g_S^{\uparrow\downarrow}+g_B^{\uparrow\downarrow}(g_S-2g_S^{\uparrow\downarrow})\cos^2\theta}. \tag{2}$$

A steady state with finite θ exists when $L_B(\theta)$ equals an external torque, either from an applied magnetic field, or a spin accumulation from the upper side in Fig. 1. The differential source–drain conductance $\tilde{G}_{SD}$ subject to the condition of a constant external torque reads:

$$\tilde{G}_{SD}\equiv\left(\frac{\partial I_{SD}(\theta)}{\partial\mu_S}\right)_{L_B}=\frac{I_{SD}}{\mu_S}+\left(\frac{\partial I_{SD}}{\partial\theta}\right)_{\mu_S}\left(\frac{\partial\theta}{\partial\mu_S}\right)_{L_B}, \tag{3}$$

$$=\frac{I_{SD}}{\mu_S}-\left(\frac{\partial I_{SD}}{\partial\theta}\right)_{\mu_S}\frac{L_B(\theta)}{\mu_S\left(\frac{\partial L_B(\theta)}{\partial\theta}\right)_{\mu_S}}, \tag{4}$$

where the first term on the right-hand sides is the derivative with respect to μ_S for constant θ and the second term arises from the source–drain bias dependence of θ. The general equations are unwieldy and not transparent. The most important parameter turns out to be the spin polarization p_S of the source and drain contacts. We, therefore, choose a model system with p_S variable, but other parameters are fixed for convenience, viz. the same parameters for both spin–flip transistors and $g_B^{\uparrow\downarrow}=g_S^{\uparrow\downarrow}=g_S$, which holds approximately for metallic interfaces with identical cross sections.[8] We find that

$$\tilde{G}_{SD}=\frac{e^2}{h}\,\frac{g_S}{2}\left(1-p_S^2\frac{2+\cos^2\theta+\dfrac{4\sin^2\theta}{2-\cos^2\theta}}{4-\cos^2\theta}\right), \tag{5}$$

may become negative, since an increased source–drain bias tends to rotate the angle to smaller values, thus reducing the source–drain current. At the sign change of $\tilde{G}_{SD}$, the output impedance of the spin valve becomes infinite, which can be useful for device applications.

We now demonstrate that it is attractive to modulate I_{SD} by the spin-transfer effect.[5,6,11] In contrast to the work in literature that focused on magnetization reversal by large currents,[7] we envisage controlled rotations by small voltages. The base is supposed to be highly resistive, consisting of a magnetic insulator, or, alternatively, of two magnetically coupled ultrathin magnetic films separated by a thin insulator. The device might be realized in a lateral thin-film geometry,[3] using a soft magnet with a circular disk shape for the base, sandwiched in a cross configuration of normal metal films with ferromagnetic contacts. The device characteristics can be computed for the complete parameter space by the circuit theory, but the important features are retained by proceeding as just mentioned and also assuming the same parameters for the upper and lower sections. The stationary state of the biased spin-transfer transistor is described by the angle θ_0 at which the two torques on the base magnet cancel each other. For the present model, this is the solution of the transcendental equation

$$\frac{\mu_B}{\mu_S}=\frac{7+\cos(2\,\theta_0)}{7-\cos(2\,\theta_0)}\tan\theta_0. \tag{6}$$

The calculated source–drain differential conductance (now without tilde) has to be computed now under the condition of constant μ_B rather than a constant torque

$$G_{SD}\equiv\left(\frac{\partial I_{SD}(\theta)}{\partial\mu_S}\right)_{\mu_B}=\frac{I_{SD}}{\mu_S}+\left(\frac{\partial I_{SD}}{\partial\theta}\right)_{\mu_S}\left(\frac{\partial\theta}{\partial\mu_S}\right)_{\mu_B}, \tag{7}$$

which is plotted as a function of μ_S and polarization p_S in Fig. 2. Note that with increasing p_S, strong nonlinearities develop which for large polarizations lead to a zero and negative differential resistance at $\mu_B\approx\mu_S$. The physical reason is the competition between the ohmic current, which for constant resistance increases with the bias, and the increasing torque, which at constant μ_B decreases the current, as noted above.

The differential transconductance measures the increase of the source–drain current (at constant μ_S) induced by an increased chemical potential of the base electrode $T(\theta)\equiv(\partial I_{SD}(\theta)/\partial\mu_B)_{\mu_S}$. We focus the discussion here on the differential current gain, i.e., the ratio between differential transconductance and channel conductance $\Gamma=T/G_{SD}$, as a

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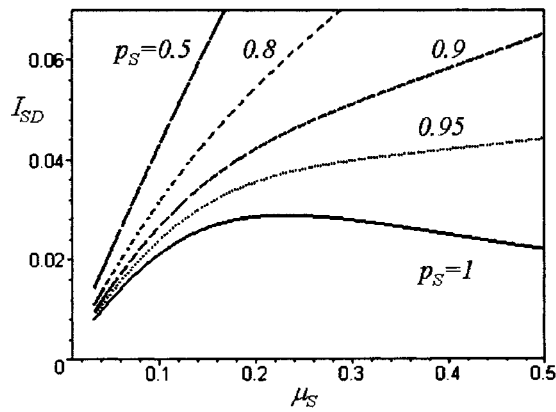

FIG. 2. Source–drain current Eq. (1) of the spin-transfer transistor, divided by the contact conductance $e^2 g_S/h$, i.e., in (voltage) units of μ_S/e, as a function of μ_S, and the polarization p_S of the source and drain contacts. A constant $\mu_B=0.2$ (in the same units as μ_S) is applied.

representative figure of merit. In the regime $\mu_B \ll \mu_S$ and thus small $\theta_0 \to 3\mu_B/(4\mu_S)$, the current gain becomes

$$\lim_{\mu_B \to 0} \Gamma = \frac{\frac{1}{2}\theta_0}{\frac{1-p_S^2}{1+p_S^2} - \frac{1}{3}\theta_0^2}. \tag{8}$$

For small polarizations, the θ_0^2 term in the denominator may be disregarded and $\Gamma \sim \theta_0$, and thus is proportional to the control potential μ_B. When the polarization is close to unity, however, we see that Γ becomes singular at small angles and changes sign. This behavior reflects the negative differential resistance found for larger μ_B and θ. For complete polarization $(p_S=1)$ $\Gamma = -3/(2\theta_0)$. For polarizations (slightly) smaller than unity, we may tune the transistor close to the optimal operation point of infinite output impedance

$$\theta_{0,c} = \sqrt{3\frac{1-p_S^2}{1+p_S^2}}, \tag{9}$$

at which $\Gamma \sim (\theta_0 - \theta_{0,c})^{-1}$.

The working principle of this spin-transfer transistor is entirely semiclassical, thus robust against, for example, elevated temperatures. The derivations assumed the absence of phase coherence and electron correlation, but the physics most likely survives their presence. The base contact is preferably a magnetic insulator or contains two magnetic films coupled through a thin insulating barrier, but the contact to the normal metal should be good (for a large mixing conductance). Tunnel junctions may be used for the source–drain contacts, but this will slow down the response time. It should be kept in mind as well that the dwell time of electrons in the device must be larger than the spin–flip relaxation time. The basic physics, such as the nonlinearity of the source–drain conductance in Fig. 2, should be observable for conventional ferromagnetic materials. Large current gains exist for incomplete polarization close to unity of the source and drain ferromagnets, but at the cost of nonzero "off" currents. A useful device should therefore be fabricated with (nearly) half-metallic ferromagnets[12] for sources and drains. As a base magnet, a thin film of any soft ferromagnet is appropriate as long as it is thicker than the ferromagnetic (transverse spin) coherence length, but not too thick in order to keep the response to torques fast. We recommend a couple of monolayers of permalloy on both sides of a very thin alumina barrier.

In conclusion, we propose a robust magnetoelectronic three-terminal device which controls charge currents via the spin-transfer effect. It can be fabricated from metallic thin films in a lateral geometry, but its usefulness will be derived from the availability of highly polarized (half-metallic) ferromagnets.

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