An amplifier concept for spintronics

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Typical spin-dependent devices proposed for information processing lack one of the most important features provided by charge based logic: they do not provide gain. In this letter we show the basic concept of a spin amplifier and propose ways to amplify a spin current at room temperature. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2977964]

Today's electronic circuits are charge based. Despite the fact that such systems are implicitly founded on the fact that electrons have spin 1/2 and are therefore Fermions, the explicit use of the spin for electronics, so-called spintronics, is still at an infancy stage. Presently, the most important spintronics device is the spin valve, which can be used either as a magnetic memory cell or a sensor.[1–3] In general, one may envision a variety of devices that are based on the electron spin as the sensor, carrier of processor of information.[1,4] A key issue in such spin based electronics is the decay of the spin polarization over a rather short distance, the spin diffusion length. In metals the decay length is especially short, e.g., $\lambda_s \approx 350$ nm for Cu at room temperature.[5] The amplification of the spin polarization has remained one of the grand challenges of spintronics. Similar as for charge based devices, it is inconceivable to imagine a complex spin based system suitable for information processing without the possibility of a spin amplifier that enables using the output of one device to control the input of many other devices.

In this paper, we consider a model spin amplifier in order to conceptually identify the basic building blocks and processes needed to amplify a spin current. Later we show that a spin current amplifier can be constructed using a spin injection pillar. The different building blocks of the model spin amplifier can be represented as different time steps in the amplification process. A similar device has been proposed.[6] While our proposed device is based on similar principles, it does not require a ferromagnetic semiconductor at room temperature, which has so far proven elusive.

We define a spin polarized current in the two current model. The current contains a "spin-up" and a "spin-down" component: $\vec{I}=(I_\uparrow, I_\downarrow)$. The total charge current is $I_c=I_\uparrow+I_\downarrow$. The spin current defines how much angular momentum is carried per time and is therefore $I_s=I_\uparrow-I_\downarrow$. A spin amplifier needs to sense the sign of the input spin current I_s^{in} and generate an output spin current I_s^{out} with the same sign as I_s^{in} but $|I_s^{\text{out}}|>|I_s^{\text{in}}|$. The gain of the spin amplifier is defined as $g_s=|I_s^{\text{out}}|/|I_s^{\text{in}}|$. A spin current amplifier is *linear* if $I_s^{\text{out}}=g_s I_s^{\text{in}}$ for all possible values of I_s^{in}. However, linearity is not required for most logic applications of spintronics since common digital electronic systems are based on nonlinear amplifiers.

One can conceptually construct a spin amplifier from well known building blocks: The first stage consists of a spin detector which senses the spin polarization of the input spin current I_s^{in} and converts it into an electrical signal. This signal is then amplified and used to drive a spin polarized current source. A possible realization is shown in Fig. 1. The input spin current is sensed by a normal metal-ferromagnet junction. This method of spin current detection has been demonstrated by Jedema *et al.*[7] as part of a nonlocal spin valve. If one brings a ferromagnet (magnetized parallel to the quantization axis) into contact with a conductor carrying a spin current, a (charge-)voltage V builds up that is proportional to the spin current. A conventional differential amplifier can be used to detect and amplify this voltage and generate a charge current $I_c \propto V \propto I_s^{\text{in}}$ of several mA. A spin current source (here realized as part of a nonlocal spin valve[7]) is used to transform a charge current to the output spin current $I_s^{\text{out}} \propto I_s^{\text{in}}$.

This model spin amplifier is ideal as it can even be constructed as a linear device and its gain is just limited by the signal to noise ratio of the electronic amplifier as well as the thermal noise of the spin detector. However, this "device" is rather complex and relies mainly on charge based electronics. In fact, the charge current amplifier is the most complex and largest part of this spin amplifier, questioning the justification for spin based signal processing.

Although the model spin amplifier is not useful as a practical device, we learn the function of the three basic building blocks of a spin amplifier: a spin detector, an amplifier, and a spin current source. In our model spin amplifier, these parts are separate building blocks which exist and act simultaneously. In the following, we will discuss the possi-

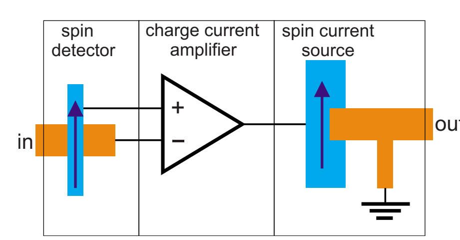

FIG. 1. (Color online) Spin amplifier constructed from well known components. The spin current polarization is detected by a spin valve and transformed into a voltage. A conventional amplifier is used to generate a charge current proportional to the detected spin current. A spin current source transforms the charge current into the output spin current.

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bility of having *one* building block that fulfills all the functions of a spin amplifier in sequence: It acts as a spin detector, amplifies the detected spin signal and later acts as a spin current source. A clock signal defines how to separate these three phases in time.

The magnetization of a ferromagnet can be manipulated by the injection of a sizable spin current.[8–10] This offers the possibility to measure an incoming spin current that is large enough. On the other hand, if we pass an unpolarized charge current through a ferromagnet, the current gets spin polarized. The only missing property to build a spin amplifier is the amplification stage: The achievable output spin current needs to be larger than the input spin current. The problem is that the magnetization of the ferromagnet will get destabilized while polarizing the output spin current. To prevent that, we need an additional control parameter, a "clock" signal which changes the stability of the ferromagnet. The amplification process has to be divided into three phases.

During the first phase, the stability of the ferromagnet is reduced. In this "sensing" configuration, the state of the system is ideally at a bifurcation point. At such a point, the magnetization is highly unstable and a minute excitation decides into which direction the magnetization relaxes later. The input spin current leads to a deviation of the magnetization from its original direction, breaking the symmetry at the bifurcation point. In a second phase, the control parameter is used to bring the magnetization into a stable configuration. As soon as the magnetization is in a stable configuration, a large unpolarized current can be polarized by the ferromagnet. As the spin polarization of the output current can be larger than the input spin polarization, a spin gain can be reached. The control parameter must be chosen carefully as it must not be directional along the axis of quantization: The symmetry of the device must only be broken by the input spin polarization.

The most prominent bifurcation in magnetism is the phase transition at the Curie temperature T_C. Especially in two dimensional systems near T_C, minute applied magnetic or exchange fields will lead to ordering along the field direction.[11] Injecting a spin polarized current into a ferromagnet at T_C is expected to have a similar effect: The injected spin current will become partially depolarized due to precession and dephasing in the exchange field inside the ferromagnet. As angular momentum is conserved, the angular momentum of the injected spins will get transferred to the ferromagnet. As explained in Ref. 6 the ferromagnet is expected to order along the injected spin polarization. If at the same time the ferromagnet is cooled below T_C, permanent ordering along the spin direction is expected to occur. This magnetic order in the ferromagnet can be used to polarize a larger current than the input of the device. Changing the temperature of the ferromagnet is not practical for a real device. The device proposed in Ref. 6 uses the electric field dependence of T_C in a ferromagnetic semiconductor.[12] This approach has not been realized as a device so far. The main technical problems with this approach are the lack of available magnetic semiconductors at room temperature as well as the requirement to keep the temperature precisely constant for successful device operation as T_C has to be reached with high accuracy in order to obtain a large spin gain.

Another bifurcation effect in magnetism can be observed in magnetodynamics. In a single domain ferromagnetic disk with uniaxial anisotropy along the x coordinate, two stable directions for the magnetization $\vec{M}$ exist. For small damping and on the time scale of the precessional motion, the magnetization vector moves along a trajectory of constant energy. As shown in Ref. 13, the trajectories for magnetization precession can be divided into three classes. The trajectories of $\vec{M}$ with low energy are located close to the energy minima $\vec{M}_x$ or $\vec{M}_{-x}$ and will eventually be damped into one of the minima. These *localized* trajectories are spatially separated from each other and cannot lead to switching of the magnetization from one minimum to the other. Trajectories with higher starting energy are not associated with one of the minima and can be used to switch the magnetization by precession. These nonlocalized trajectories will eventually damp and become localized, an essential part of magnetic switching. These three classes of trajectories are separated by special lines, the separatrices. As soon as the magnetization crosses from a nonlocalized trajectory over one of the separatrices, it becomes localized and its equilibrium magnetization direction is defined. The crossing points of the two separatrices are of great interest for this discussion as these are bifurcation points $\vec{M}_{b1,2}$: If the magnetization is brought to a bifurcation point by a magnetic field pulse, a small deviation of the magnetization decides if $\vec{M}$ relaxes to $\vec{M}_x$ or $\vec{M}_{-x}$. Figure 2 shows conceptually how this bifurcation point can be used to realize a spin amplifier.

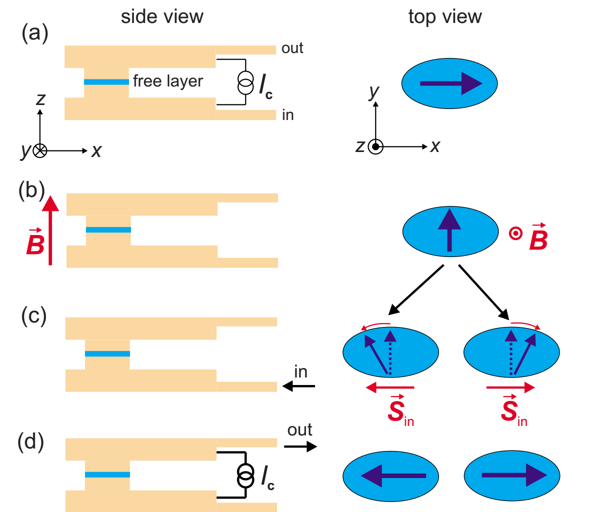

FIG. 2. (Color online) (a) The amplification stages of the spin amplifier implemented as an elliptical ferromagnetic layer. (b) A field pulse lets the magnetization precess into the bifurcation point. (c) The input spin current breaks the symmetry of the bifurcation point. (d) The magnetization relaxes into the static configuration given by the input spin current. In this configuration, the ferromagnet can act as a polarizer for the output spin current.

In a ferromagnetic thin disk in the x,y plane with easy axis shape anisotropy along the x axis, the bifurcation points $\vec{M}_{b1,2}$ are on the y axis. In a first step, a well timed magnetic field pulse is applied along the z direction to ballistically (through precession) move the magnetization into one of the bifurcation points. Now, the spin amplifier is in its sensitive configuration. In a second step, the input spin current I_s with its spins $\vec{S}_{in}$ aligned in the direction x or $-x$ is injected into the ferromagnet. The injected spins will precess around M and dephasing will lead to a transfer of their angular momenta to M. As the angular momentum transfer is along the x or $-x$ direction, the symmetry is broken, $\vec{M}$ will leave the bifurcation point and relax into the x or $-x$ direction depending on the direction of $\vec{S}_{\text{in}}$. As the magnetization of the ferromagnet relaxed into the equilibrium configuration it can serve as a polarizer for an unpolarized current. Its stability given by the shape anisotropy makes it possible to polarize a larger current than the input spin current needed for symmetry breaking. Therefore, this system provides spin gain.

It is challenging to demonstrate the proposed device as precise control of ultrafast field pulses is required in order to bring the magnetization into the bifurcation point. The spin amplifier concept can be demonstrated in a much simpler way by working on a time scale much longer than given by the precessional motion. The field pulse in the concept above is replaced by a variable dc magnetic field along the y axis. The field can be chosen to be large enough to almost overcome the shape anisotropy. In this state, the energy barrier between the two stable configurations is reduced, bringing the ferromagnet into the sensing configuration. Reducing the dc bias field to zero, the magnetization is in the most stable configuration and can act as a polarizer.

To demonstrate this effect, we investigated the switching current of a spin transfer pillar structure as a function of the applied field along the hard direction in the plane of the layers. The samples consist of typical current-perpendicular-to-plane spin valve nanopillars with a size of 100×70 nm^2. The fabrication process can be found in Ref. 14. The free layer consists of 2 nm of $Co_{0.86}Fe_{0.14}$ and a 3.5 nm Cu spacer separates the free layer from the fixed, polarizing layer. This fixed layer consists of a CoFe (1.8 nm)/Ru (0.8 nm)/CoFe (2.0 nm) synthetic antiferromagnet (SAF). The SAF is pinned by exchange bias to an underlying IrMn layer. The fixed layer would not be part of a real device: Here it is used to generate the input spin current as well as to detect the state of the free layer through the giant magnetoresistance effect. As shown in Fig. 3, the switching hysteresis depends on the applied magnetic field along the hard direction. As the field increases, the hysteresis becomes narrower. As this point, the device is sensitive to the input spin current which can switch it more easily. Once the device is switched, the field can be reduced to zero, leading to a much more stable magnetization configuration as one can see from the wider current driven hysteresis loop. In this case, the "free layer" could be used to further polarize an unpolarized or partially polarized current. Assuming a large enough spin polarization is achievable by the ferromagnet, a spin gain can be reached. The magnitude of the gain depends on the polarization generated by the ferromagnet as well as the applied unpolarized charge current.

In conclusion, we have shown the basic requirements to realize a spin current amplifier and described several ways how a spin current amplifier can be constructed. In order to reduce the complexity and size of such a device, we envision to divide the amplification process into three steps in time: spin current sensing, amplification, and polarization of the output spin current. In this sense our proposed spin amplifier acts like a D-flipflop with a fan-out of more than one (the clock signal of the flipflop divides the different steps of amplification). The concept of a spin amplifier has been introduced by[6] using the voltage dependence of the Curie temperature in a ferromagnetic semiconductor. Our proposed devices generalize this concept to bifurcation mechanisms in magnetism and lead the way to amplification of a spin current at room temperature.

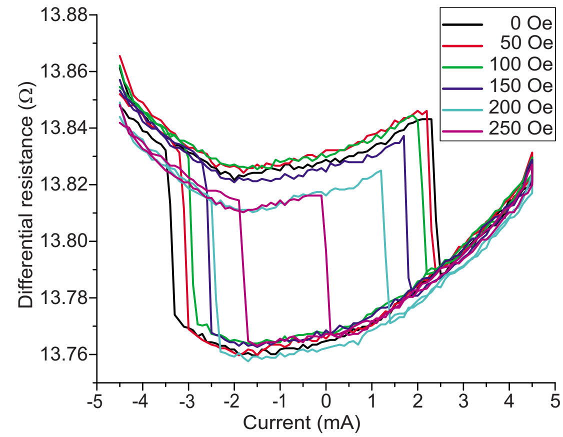

FIG. 3. (Color online) Demonstration of spin current amplification in conventional spin transfer pillars. A static magnetic field is applied along the hard direction of the free layer. Current driven hysteresis loops are measured as a function of the applied magnetic field. The magnetic field along the hard direction leads to narrowing of the hysteresis. Therefore, the free layer is in the sensing state of the spin amplification cycle. At zero magnetic field the hysteresis is wider, providing the stability to polarize the output spin current.

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