1 Title of the project

Spin current operated magnetic memory based on single ferromagnet.

2 Applicants

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References:

Master thesis

Electronic detection study of magnetization dynamics in ferromagnetic/nonmagnetic systems. Rijks*universiteit* Groningen, The Netherlands 2006

3 FOM-researchgroup

GM-G-08

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5 Abstract

Magnetoresistive memory based on ferromagnet/nonmagnet/ferromagnet stacks is non-volatile memory that can have a speed as fast as semiconductor-based memory. The main bottleneck for the use of magnetoresistive memory is the use of a magnetic field for operating the magnetic state. Recent research has focused on the use of spin polarized currents to induce magnetization dynamics and help the magnetization switching processes. On the other hand, Brataas *et. al* [1] have proposed the idea of a spin battery device, in which a spin current is pumped into an adjacent nonmagnetic conductor by magnetization dynamics. Since a ferromagnet has different conductivities for electrons with opposite spin polarization it can itself act as a detector of the spin current. We propose to carry out experimental research which will use spin polarized currents for driving magnetization dynamics of a nanomagnet, while the spin detection properties of the ferromagnet will be used for studying the impact of the magnetization dynamics on the spin dependent transport properties of the ferromagnetic/nonmagnetic metallic structures. Based on these ideas, we propose a new type of MRAM device in which spin currents are used to both write and address the state of magnetoresistive element.

6 Duration of the project

4 years, starting from October 2006.

7 Personnel

7.1 Senior-scientists

Name	Task in project	Time
Prof. Dr. Ir. B.J. van Wees	Supervision and management	5%
Dr. Ir. C. H. van der Wal	Supervision and analysis	10%

7.2 Junior-scientists and technicians

Name	Task in project	Time
PhD student (OIO)	Experiments and analysis	90%
B. Wolffs	technical support	10%
Ing. S. Bakker	technical support	5 %

8 Cost-estimates

8.1 Personnel positions

One 'onderzoeker in opleiding' position for four years.

8.2 Running Budget

15 k€/year

8.3 Equipment

No equipment is requested.

8.4 Other support

The project is part of a larger research programme of the MSC^{plus}. Involved personnel described above is employed via the MSC^{plus} or associated research programmes.

8.5 Budget summary (in k€)

The expenses are summarized in the following table

	2006	2007	2008	2009	2010	TOTAL
Personnel (positions)						
PhD students	16.4	41	41	41	24.6	164
postdocs	-	-	-	-	-	-
technicians	-	-	-	-	-	-
guests	-	-	-	-	-	-
personnel(costs)	16.4	41	41	41	24.6	164
running budget	6	15	15	15	19	60
equipment FOM-part	-	-	-	-	-	-
TOTAL(requested from FOM)	22.4	55	55	55	43.6	224

9 Introduction

High speed operation and low power consumption are requirements of modern digital electronics. Today the market of memory technologies is dominated by the Dynamic Random Access Memory (DRAM) and Flash technologies, which use an electric charge to determine the on-off state of the memory bit cell. DRAM is distinguished as a high speed memory but at the same time shows a disadvantage since it requires background refreshing due to the leakage of electrons. In contrast, the Flash memory is non-volatile, but significantly slower than DRAM.

A revolutionary memory technology which intends to replace conventional semiconductor memory is a Magnetoresistive Random Access Memory (MRAM) [2]. The effect of magnetoresistivity is defined as a slight change in electrical resistance under the application of magnetic field and is the most pronounced in Giant Magneto Resistive (GMR) and Magnetic Tunnel Junction (MTJ) structures. These structures consist of a layer of either nonmagnetic metal (GMR) or insulating material (MTJ) between two electrodes of magnetic material. One electrode is a fixed ferromagnetic layer that creates a strong pinning field to hold the magnetic polarization of the layer in one specific direction. The other ferromagnetic layer is free to rotate and hold the polarization in one of two directions. When the pinned and free layers have the same polarization, the Magnetoresistive cell will have a low resistance state. When they are antiparallel, the cell has a high resistance state. The resistance state is detected by sending current through the structure.

Conventional MRAM cells, like GMR or MTJ Fig.1(a) are based on the idea of mapping magnetic states on electrical signals by probing the resistance. This requires two layers of magnetic materials, one for reference and another one for device operation (switching magnetic state). The full writing cycle consists of two crucial steps: manipulation of the magnetic state (switching) and electrical probing of the resistance (probing).

Even though the operation speed of GMR and MTJ devices reaches the performance of DRAM, the process of “writing” the magnetic bits still remains quite cumbersome since it uses the magnetic switching field which can be hardly restricted to the location where it is needed. This leads to a waste of a lot of precious battery power and makes further miniaturization difficult.

The alternative to the magnetic switching field comes from effect of spin transfer torque which uses a spin-polarized current with electrons having the same spin direction to align the magnetization of the free layer along the current polarization direction [3].

We propose that spin current can be used for both writing and read-out Fig.1(b). It has been predicted that ferromagnet in a state of resonant magnetization precession emits spins into an adjacent nonmagnetic conductor. This effect is known as a spin battery [1]. This spin current builds-up a spin accumulation close to the ferromagnet/nonmagnetic metal interface which induces diffusive spin current back into the ferromagnet. We propose that since the

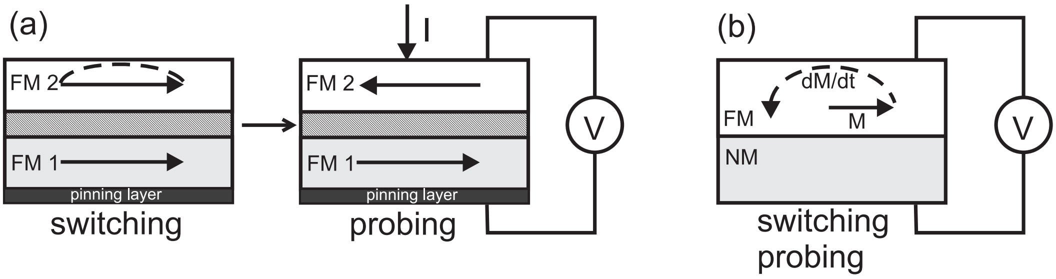

Fig. 1: (a) Typical writing operation cycle for GMR or MTJ device. At a first step, magnetization state is written either by magnetic field or by spin polarized current. Second step is an electrical read out of magnetic state by probing the resistance via sending electrical current through the structure. (b) Single ferromagnet magnetoresistive cell: switching of the magnetization and read-out are combined in a one step. In order to map magnetic state on an electrical signal we use an effect which predicts voltage generation across the FM/NM interface due to the time dependent magnetization.

conductivities for spin-up and spin-down electrons in ferromagnet are different, it acts as a spin detector resulting in a voltage drop across the FM/NM interface.

Therefore, when spin polarization of the current is parallel to the magnetization direction of the ferromagnet, no voltage will appear across the FM/NM interface since no torque will be created on the magnetization. This will correspond to the "0" bit or "off" state. In the opposite case, when spin polarization and magnetization are antiparallel, spin torque will induce magnetization motion which will generate voltage across the FM/NM interface due to the spin battery effect, indicating "1" bit or "on" state.

The interplay between spin polarized transport and magnetization dynamics in ferromagnets is crucial to understand the spin torque and spin pumping effect. The role of nonmagnetic material and spin dynamics there starts to be quite complex since it has to accommodate significant spin accumulation for generating large enough back flow spin current while in GMR type of devices nonmagnetic region was used only for transferring spin polarized current.

We propose a new class of magnetoelectronic devices, which demonstrate the simultaneous use of the ferromagnet as a spin source and spin detector and based on a mutual interaction between magnetization dynamics and spin transport close to the ferromagnet/nonmagnetic metal interface.

10 Research programme

10.1 Goal of the proposal

The proposed research aims at demonstrating that a single ferromagnet can act as a spin current source and the spin current detector at the same time. The project therefore addresses the following two fundamental questions:

1. It was predicted that a ferromagnet under resonant magnetization dynamics serves as a source of spin current. Is it possible to use the same ferromagnet as a detector of this current?

2. Research has seen strong development in switching the magnetization of the ferromagnetic layer by the spin polarized current due to the spin torque mechanism. Is it possible to use switching dynamics of magnetization to drive spin current into adjacent nonmagnetic conductor?

Answering these two question requires the on-chip investigation of the magnetization dynamics in ferromagnets on a submicron size scale and research with different nonmagnetic materials in $NM_1/FM/NM_2$ structures.

This proposal addresses the following research lines:

- Design and fabrication of samples with spatially localized time alternating magnetic field for driving magnetization dynamics with a large precession amplitude.
- Design and fabrication of the on-chip $NM_1/FM/NM_2$ coplanar structure with controllable properties of the $FM/NM_{1,2}$ interfaces for investigating the role of the interface in mutual interaction between magnetization dynamics in ferromagnet and spin accumulation in nonmagnetic region.
- Design of the experiment which will allow to separate and elucidate different magnetoresistive and current induced magnetization dynamics effects and their interplay in scope of MRAM application.

10.2 Spin transport through FM/NM interface

The phenomena we intend to study requires the application of a spin polarized current in order to produce spin accumulation, a non equilibrium magnetization (or spin) density. The first experiments on spin injection, spin transport and spin manipulation date back to 1985, when Johnson and Silsbee observed the transport of spin polarized current in single crystal of Al at low temperature [4].

Nowadays the spin polarized current is not exotic anymore and has been observed even at room temperature in diffusive nonmagnetic metals like Cu or Al [5].

Spin polarized current is usually created by sending a charge current through the FM layer, which acts as a spin filter due to the different conductances for spin-up $|\uparrow\rangle$ and spin-down $|\downarrow\rangle$ electrons, with respect to the quantization axis.

One can expect that the spin polarization of the current injected into NM will be defined by the difference in conductances for electrons with opposite spin polarity. In reality the spin polarization was found to be much smaller due to the so-called conductance mismatch problem [6], where all the spin dependent properties of FM/NM interface are suppressed by the resistance originated from the band alignment in FM and NM.

Highly efficient generation of the spin polarized current is a challenging problem for spintronics. This challenge can be faced by the mechanism of spin injection driven by the magnetization dynamics.

10.3 Spin current induced torque

In this section we introduce an effect which demonstrates the strong impact of spin current on magnetization dynamics.

The spin polarization of an electron can be defined as either spin-up or spin-down with respect to the quantization axis, *e.g.* z-axis. At the same time, the linear combination of these states still is a proper spinor wave function. For example $(|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$, representing a spin pointing in the positive x-direction and $(|\uparrow\rangle - i|\downarrow\rangle)/\sqrt{2}$ represents a spin pointing in the positive y-direction. This reflects the fact that any spin state can be defined only with respect to a particular quantization axis, which is usually free to be chosen.

When one is talking about a ferromagnetic metal then it is convenient to chose the spin quantization axis to be along the direction of the equilibrium magnetization.

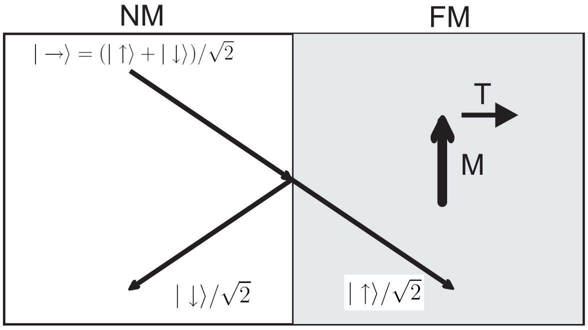

Fig. 2: Schematic representation of the spin transfer of an incoming electron with spin state $|\rightarrow\rangle$ from a non-magnetic region NM to a ferromagnetic region FM. M is the magnetization direction, T is the direction of the torque acting on M.

If a ferromagnet is in contact with nonmagnetic conductor, then one can think about the situation when spins polarized transverse to the magnetization attempt to enter the ferromagnet. This is possible, for example, when current is sent through a $FM_1/NM/FM_2$ structure, in which the first ferromagnet (FM_1) acts as a spin polarizer and has a magnetization direction orthogonal to that of second ferromagnet (FM_2).

We assume for simplicity that FM_2 is "half metallic", such that only $|\uparrow\rangle$ states are allowed there. Since the state of the incoming electron can be represented as a linear superposition of FM_2 states, the problem can be considered in the framework of a scattering problem. As shown in fig.2, component $|\uparrow\rangle$ will enter FM_2 while component $|\downarrow\rangle$ will be reflected back into NM. This has an important consequence: the transmitted electron has a spin pointing in the positive z-direction while the spin of the reflected electron points in the negative z-direction. This situation can be seen as the spin component perpendicular to $\vec{M}$ has been lost. However, due to the conservation of angular momentum it must imply that angular momentum is transferred from NM region to the ferromagnet FM_2. The transferred angular momentum creates torque on the magnetization in the direction of the incident polarization of the incoming spin. It has been shown that this torque can induce magnetization reversal, can drive magnetization dynamics and can be used for rectification of the spin current [3].

10.4 Spin pumping and mixing conductance

Recently the opposite to the spin torque effect was predicted and named spin pumping [1].

When the vector of magnetization of ferromagnet obeys processional dynamics, it results in the injection of spins into an adjacent NM conductor. This mechanism allows the injection of pure spin current, which means that there is only net angular momentum flow through the FM/NM interface, while the net charge current is equal to zero. This mechanism is also free of the conductance mismatch problem.

Spin pumping effect can be seen as a loss of angular momentum from the FM, whose magnetization is undergoing resonant precession. In terms of quantum mechanics, ferromagnetic resonance corresponds to the population of the spin-down $|\downarrow\rangle$ state, while the dissipation processes tend to bring the system back into the ground state which corresponds to the population of the spin-up $|\uparrow\rangle$ state. The excess population of the $|\downarrow\rangle$ state can be reduced by transferring angular momentum into the adjacent NM conductor, which is done by injecting spin current.

It is important to note that spin torque and spin pumping effect have the same physical origin, which in the scattering framework is described by the so-called spin mixing conductance. The spin mixing conductance represents the probability to scatter spin states transverse to the

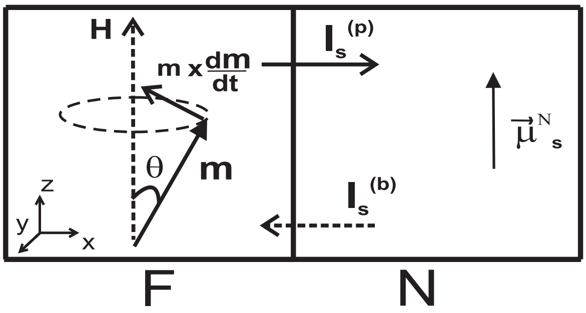

Fig. 3: Schematic illustration of FM/NM interface. The ferromagnet due to the precessional dynamics pumps spin current into normal metal - $I_s^{(p)}$, this builds-up spin accumulation - μ_s^N, which induces back flow spin current into FM - $I_s^{(b)}$

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quantization axis into either a spin-up or spin-down state. In the Valet and Fert two channel model [7], the spin mixing conductance is introduced as the non-diagonal element of the spin conductances matrix.

10.5 Single ferromagnet as a source and a detector of spin current

Since a spin current is a flow of angular momentum, it does not have to be conserved. When spins are injected through a FM/NM interface, they create spin accumulation in NM which extends by a distance of the order of the spin flip length $\lambda_{sf} = \sqrt{D\tau_{sf}}$, where D is the electron diffusion coefficient and τ_{sf} is the spin flip time [1].

Spin accumulation close to the interface induces diffusive spin current back into FM which now acts as a spin detector Fig.3. When a spin current is flowing into FM, it can be seen as two electrons with different spin polarization, where one is entering FM while another one is leaving. In a FM, conductivities for spin-up and spin-down electrons are different, which means that processes of entering and leaving FM occur at different rates, resulting in charge accumulation close to the FM/NM interface. In an experiment this will appear as a voltage drop across the interface.

It is clear that for inducing the large back flow spin current into a ferromagnet, a large spin accumulation in the nonmagnetic metal is required. This can be achieved by choosing a nonmagnetic metal with a large spin flip length or by making an interface which will ensure effective spin emission.

10.6 Magnetoresistive memory based on single ferromagnet

A schematic drawing of elementary device that allows to study the phenomena of spin torque and spin pumping is shown at fig.4. A ferromagnetic strip is positioned close to the coplanar waveguide (CPW) which is used for creating radio-frequency (rf) magnetic field. External magnetic field is applied along the strip for satisfying ferromagnetic resonance conditions. Ferromagnet is connected by two nonmagnetic metal leads which can be made from a different materials (e.g. with a different spin diffusion length) and with a different properties of FM/NM interface as well (e.g. clean contact or tunnel junction).

This type of structures can be made by means of the Electron Beam Lithography (EBL) with a lift-off in combination with Optical lithography for a large patterns. Different properties

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[1] The spin flip length is sometimes called the spin diffusion length, since this parameter determines the distance that a spin can diffuse before it will flip its state.

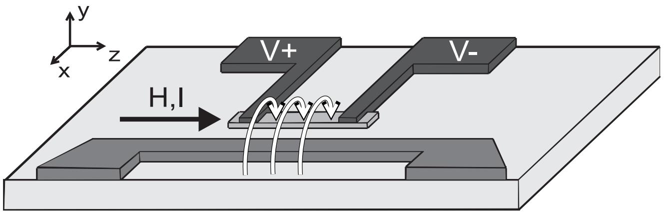

Fig. 4: Schematic drawing of the device for studying spin torque and spin pumping effect.

of contacts can be achieved by using either Kaufmann etching for creating clean contact or shadow evaporation technique for creating tunnel junction.

Using this structure, two different experiments can be realized.

In the first, magnetization precession is driven by the rf field. At resonance it induces spin current into nonmagnetic leads due to the spin pumping effect. If spin diffusion length of the NM leads are different it leads to the different voltage drop across FM/NM interfaces, which is measured as $V_+ - V_-$. This experiment is served to demonstrate the usability of the FM as a spin source and spin detector at the same time.

In the second experiment, magnetization dynamics can be driven by the spin polarized current I_s sent through the additional contacts to the FM strip (not shown at the picture), while CPW can be used as a detector of the magnetic flux created by the precessing magnetization. Nonmagnetic leads are used to detect the spin pumping effects. This experiment is intended to demonstrate the applicability of the switching dynamics of magnetization to drive spin current into nonmagnetic leads.

As a ferromagnetic material we are planning to use permalloy ($Ni_{20}Fe_{80}$) since it has a small coercive field and vanishing crystal anisotropy. This would result in a high amplitude magnetization precession and easy magnetization switching process.

As materials for normal leads the good candidates are Cu and Al with a long spin flip length and Pt with a short spin flip length. Al will be also used in experiment with tunnel junction since we have a developed procedure in creating thin oxide Al layer during the shadow evaporation process.

Proposed experiments also will be used for experimental determining such an important parameter for interplay between magnetization dynamics and spin transport as the spin mixing conductance and its dependence on the materials and properties of interface.

11 Infrastructure

The Physics of nanodevices group has a variety of processing and measuring facilities. For this project the most important facilities are:

- A cleanroom equipped with general processing facilities such as a mask aligner, an e-gun evaporator and a reactive ion plasma etcher
- An e-gun evaporator with Kaufmann etching source
- A Raith e-line electron beam lithography system
- A JEOL inspection scanning electron microscope
- An RF setup for experiments on electronic detection of magnetization dynamics with measurements equipment such as: RF source, spectrum analyzer, electrical magnets, lock-in amplifiers, multimeters, RF amplifiers etc.

We are planning to extend our sample preparations and measurements facilities by realizing:

- Deposition of ferromagnetic and nonmagnetic metals using sputtering technique.
- A cryostat (77-300K) with air flow control for temperature dependent measurements.
- Free for an in-plane rotation magnet stage for an angle dependent measurements.

All these setups and enhancements are not included in this proposal and will be financed by other means.

12 Application perspective in industry, other disciplines or society

In the proposed research, we intend to improve and extend the use of the spin currents in magnetization switching processes. We propose a new paradigm for magnetic memory technology, in which all aspects of operation are based entirely on spin polarized currents and their interaction with magnetization dynamics. The simultaneous use of single ferromagnet as a spin current source and spin current detector could lead to the significant reduction of the writing cycle time, while truly non volatile technology will make this memory to be highly competitive with a volatile semiconductors analogs.

References

[1] A. Brataas, Y. Tserkovnyak, G. E. W. Bauer, and B. Halperin *Phys. Rev. B*, vol. 66, p. 060404, 2002.

[2] J. Akerman *Science*, vol. 308, p. 508, 2005.

[3] T. Kimura, Y. Otani, J. Hamrle, Phys. Rev. Lett. 96, 037201 (2006), E. B. Myers, D. C. Ralph, J. Katine, R. N. Louie and R. A. Buhrman, Science 285, 867, (1999), I. N. Krivorotov, N. C. Emley, J. C. Sankey, S. I. Kiselev, D. C. Ralph and R. A. Buhrman, Science 307, 228, (2005), A. A. Tulapurkar, Y. Suzuki, A. Fukushima, H. Kubota, H. Maehara, K. Tsunekava, D. D. Djayaprawira, N. Watanabe and S. Yuasa, Nature 438, 339, (2005).

[4] R. H. Silsbee, A. Janossy, and P. Monod *Phys. Rev. B*, vol. 19, p. 4382, 1979.

[5] F. J. Jedema, A. T. Filip, and B. J. van Wees *Nature*, vol. 410, p. 345, 2001.

[6] G. Shmidt, D. Ferrand, L. Molenkamp, A. T. Filip, and B. J. van Wees *Phys. Rev. B*, vol. 62, p. 4790, 2000.

[7] T. Valet and A. Fert *Phys. Rev. B*, vol. 48, p. 7099, 1993.