

# Spin Valves For Innovative Computing Devices And Architectures

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## Abstract

Spin valves are spintronic devices that can potentially serve as both non-volatile storage elements and programmable logical units. This offers tremendous possibilities for computing and storage devices. They consist of two ferromagnetic layers which can be oriented parallel or anti-parallel to each other. Both states have a different resistance allowing for digital electronic applications. In this work some theoretical fundamentals of spin valves are briefly sketched. From these basic requirements are derived which equivalent electrical circuits have to fulfill. Micromagnetic simulations can serve to provide the model parameters for the SPICE models, but are not appropriate to compute the electrical interaction of many spin valve elements. A prototype for an electric circuit model and first results are presented.

## 1. INTRODUCTION

In every discipline of science and technology researchers want to go beyond today's limits to get a deeper understanding of nature. This quest is facilitated nowadays by the advent of powerful computers that allow for complex computer simulations. The advancement of computers itself has become a driving force in the research and engineering of semiconductor and magnetic materials. From the very beginning programmable computers were in use when Zuse and von Neumann developed their computers in the 1940's. Since then, this field has developed tremendously with an annual growth rate of 80% in computing power (FLOPS) [1]. In principle there are two possibilities to augment computers: improving a computer's architectural concept or improving its components. Pipelining in reduced instruction set (RISC) computers is one successful example for improving a computer's architecture. The increment of a processor's clock speed is a very common example of a technological improvement of the components. Gordon Moore's law is a well known prediction for the exponential increase of transistors on a chip. Since its publication in the early sixties, it has been appropriate for more than forty years [2].

So far, this increase has scaled with growing computing performance. In order to maintain this enormous growth of computing performance in the future, industry and academia are investigating new computer architecture concepts as well as alternative options that implement new computing devices. One current enhancement in computer architecture are multi-core processors, but there exist other parallel computer architectures, like the Cell broadband engine that was recently developed in a joint venture of Sony, Toshiba and IBM [3]. Another example is the TRIPS machine [4], which is being developed at the University of Texas at Austin. These examples indicate that the future of computing could be the parallel processing paradigm.

Furthermore, there arises a transition from the universal software-controlled computer to the reconfigurable computer as indicated for example by the International Technology Roadmap for Semiconductors [5,6]. There is a conflict between the flexibility of a general purpose machine and the optimum performance of an application-specific integrated circuit, which is optimized for a given application. Reconfigurable computers could overcome this discrepancy, because they would allow to be optimized for every task.

A prerequisite for a reconfigurable computer are reconfigurable hardware devices. At present, these are realized via programmable interconnects in field-programmable gate arrays (FPGA). Spin valves seem to be good candidates for non-volatile memory devices since they are already sold as magnetoresistive random access memory devices (MRAM) [7]. They have also been suggested as nanometer-size programmable logical units (nPLUs) to perform logical operations [8]. These elements could also be used for nanoscale FPGAs in reconfigurable hardware.

A spin valve is a device built of two magnetic layers and a non-magnetic (either a conductor or an insulator) layer in between, similar to a read head in a modern hard-disk. The magnetization in one layer is fixed while the magnetization in the other layer can be switched. In a spin valve symbols are represented by the magnetization in the layers relative to each other. Besides its charge, an electron possesses also a spin that can influence the magnetization in a ferromagnet. These devices are non-volatile and have practically infinite read/write-cycles. In this article we show that a hierarchical modeling and simulation scheme allows a realistic prediction of the behavior of such nPLUs from a physical level

describing the behavior of a single independent spin valve [9] to the electric circuit level that describes the dynamic interaction of many cells. The ability to study the physical properties of magnetic and semiconductor solids is limited by the complexity of the physical phenomena involved which leads to high demands in computing power and storage space. We developed a prototype electric circuit, which represents the basic behavior of a spin valve. With this hierarchical scheme it is possible to use the SPICE simulator [10] which in principle can handle electrical systems of unlimited size.

This article is organized as follows: In section 2 a brief theoretical background of spin valves is provided. The approach to simulate an exemplary spin valve is shown. Section 3 covers the design and the dimensioning of an electric circuit as well as the results that were obtained inform the SPICE simulation. We conclude in section 4 with an outlook.

## 2. THEORETICAL CONSIDERATIONS

Magnetism in a solid is caused by electrons due to their angular momentum and their spin. Magnetism can be described in terms of a magnetic moment, which is a measure for the strength of the magnetic field generated by the electrons [11]. Often, another quantity is used instead of the magnetic moment to describe this situation: the magnetization  $\mathbf{M}$  which is the volume density of magnetic moments.

### 2.1. The dynamics of the magnetization

The effective magnetic field in a ferromagnetic body is a combination of internal magnetic fields and applied external magnetic fields. The effective magnetic field causes the magnetization to orientate towards it. The magnetization performs a damped precession while moving towards the magnetic field as is shown in Fig. 1. The equation that describes the change of the magnetization over time is called the Landau-Lifshitz-Gilbert equation (LLG) [12, 13]:

$$\frac{d\mathbf{M}}{dt} = -\gamma\mathbf{M}\times\mathbf{H}_{eff} + \frac{\alpha}{M_S}\mathbf{M}\times\frac{d\mathbf{M}}{dt} \quad (1)$$

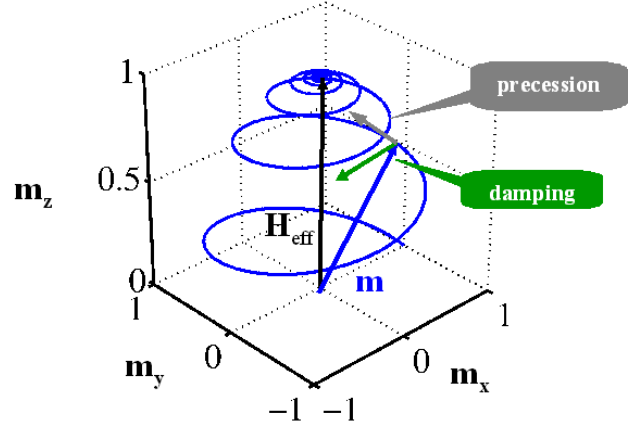
Where  $M_S$  is the saturation magnetization,  $\gamma = 2.21 \cdot 10^5$  m/As is the absolute value of the gyromagnetic ration,  $\alpha$  is the Gilbert-damping constant, and  $\mathbf{H}_{eff}$  is the effective magnetic field. Figure 1 shows the trajectory of the magnetization due to the effective field schematically.

The model that describes the magnetization dynamics via the LLG-equation and the magnetic interactions within a nano- or micrometer-sized ferromagnet is called the micromagnetic model. With the advent of powerful computers micromagnetic simulations have become a well established method for predicting and understanding the dynamics of

such systems and have proven invaluable for research and engineering in this field.

### 2.2. The giant magneto-resistance effect

As already mentioned in section 1, the magnetization in one layer of the spin valve is fixed, whereas the magnetization in the other layer can be switched; this layer is referred to as



**Figure 1.** Sketch of the trajectory of the magnetization due to its effective field showing a precession around the effective field vector as well as a damping towards it.

the free layer. The magnetic state of the free layer can be detected with the help of the so-called giant-magneto-resistance effect (GMR), where the ohmic resistance of a sample depends on the alignment of the magnetization in the free layer with regard to the fixed layer. First experimental evidence to this was given by Grünberg and Fert [14, 15]. Both were awarded with the Nobel Prize in Physics in 2007 for their work.

To use a simple explanation, if the spin of an itinerant electron is aligned anti-parallel to the spin of a localized electron that constitutes the magnetization in one of the two ferromagnetic layers of the spin valve, the probability of a scattering is higher than if the spin of the itinerant electron is aligned parallel. This situation is expressed with the so-called two-channel model [16].

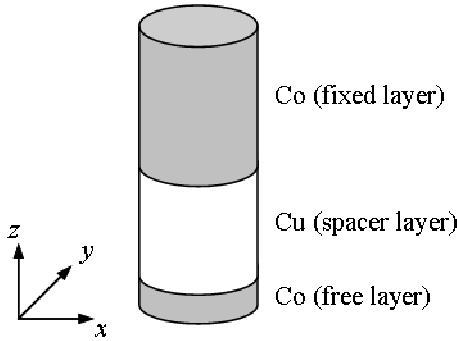
The variation of the resistance is given by:

$$GMR = \frac{\Delta R}{R} = \frac{\rho_{AP} - \rho_P}{\rho_P} \quad (2)$$

where  $\rho_{AP}$  is the resistance in case of anti-parallel alignment, and  $\rho_P$  for the parallel case. In a spin valve electrons get polarized when traversing through the fixed layer, meaning their spin is oriented to that direction. For currents flowing in the opposite direction the polarization occurs by the reflection of the electrons at the interface of the fixed layer.

In this case, the polarization is inverted. Thus currents flowing in  $+z$ -direction (as sketched in Fig. 2), with the electrons traversing from the thicker fixed layer to the free layer, exert a torque on the magnetization of the free layer that tends to align the free layer magnetization parallel to the fixed layer, while an opposite current causes an anti-parallel alignment. With these two possible states, it is possible to represent binary symbols 0, 1. This torque of the itinerant current electrons on the magnetization is called the spin-transfer torque effect in magnetic multilayers for which there exists an established theory [17] as well as Experimental evidence [18].

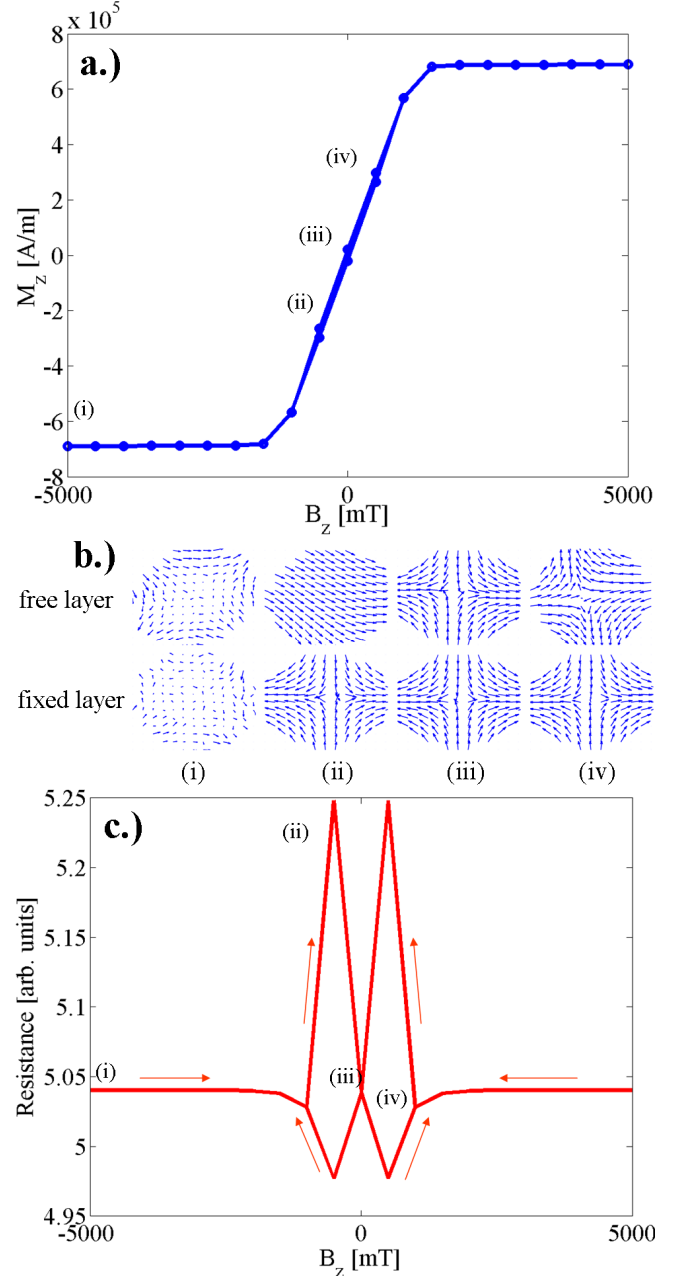
We performed micromagnetic simulations of such a spin valve, in this case a Co/Cu/Co trilayer as depicted in Fig. 2 with the help of the open-source software OOMMF [19]. The results are shown in Fig. 3. Recently, we have developed our own micromagnetic simulation software [9] to allow for a more flexible inclusion of different physical effects such as diffusive transport.



**Figure 2.** Sketch of the simulated Co/Cu/Co spin-valve. In the  $xy$ -plane the structure has a circular shape with 100 nm diameter. The free layer, the spacer layer, and the fixed layer are 3 nm, 8 nm, and 12 nm thick, respectively. An external magnetic field is applied in  $z$ -direction.

### 3. PROTOTYPE OF AN EQUIVALENT ELECTRONIC CIRCUIT

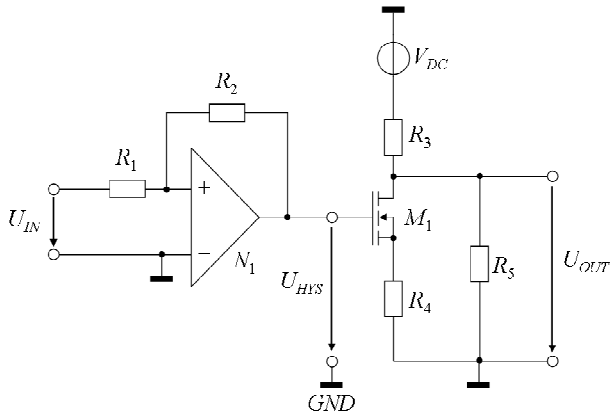
Simulators like  $M^3S$  [9] and OOMMF can simulate details of the physics of a spin-valve. For instance, the simulation allows to spatially resolve the dynamics of the magnetization in the free as well as in the fixed layer. However, if one tries to map the behavior of a spin-valve onto electrical circuit, these simulators are inappropriate. For an electrical circuit to match the behavior of a spin valve, it is necessary to identify the relevant physical parameters and map them onto electrical quantities such as voltage and ohmic resistance. Certain parameters like the geometrical dimensions of the structure also have an important influence on the behavior of the spin-valve itself that will flow into the circuit model as free parameters. There are a number of proposals



**Figure 3.** Results of a simulation of the spin valve described in Fig. 2. **a.)** Hysteresis of the  $z$ -component of the magnetization plotted against the  $z$ -component of the magnetic induction. **b.)** The magnetization pattern in the free and fixed layers at different values of the magnetic induction at the corresponding points (i) to (iv) in a.). **c.)** Resistance of the spin valve due to GMR for different values of the induction.

for an electric circuit [20, 21] the behavior of which would be equivalent to the micromagnetic model, but these do not model the hysteresis of the magnetization.

In the approach presented here, there are four relevant parameters to be mapped onto the electrical circuit: the effective magnetic field, the current, and the resistances of the spin-valve for anti-parallel and parallel orientation of the free layer as well as the hysteresis of the magnetization that depends on the magnetic field and on the current. The proposed circuit in principle matches the behavior of a spin-valve. Since it is quite complex to determine realistic parameters, in a first approach the parallel orientation of the magnetization in the free and fixed layer is mapped onto an ohmic resistance  $R_p$ , whereas the anti-parallel orientation is mapped onto an ohmic resistance  $R_{AP}$ . The hysteresis of the magnetization is represented by a non-inverting Schmitt-Trigger. Finally, it is possible to switch between the two resistances with an N-MOS-transistor in a voltage divider with the transistor as its load. The circuit is shown in Fig. 4.



**Figure 4.** Sketch of the circuit design.  $R_1$ , to  $R_5$  are ohmic resistors,  $N_1$  is an operational amplifier, and  $M_1$  is an N-channel-MOS transistor in enhancement mode.  $V_{DC}$  is a DC-voltage source,  $U_{IN}$  the input voltage, and  $U_{HYS}$  the output of the Schmitt-Trigger.  $U_{OUT}$  is the output signal of the circuit.

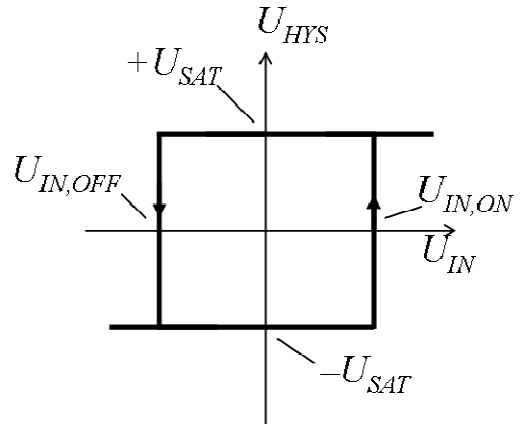
### 3.1. The hysteresis circuit

The Schmitt-Trigger is a threshold switch and is carried out with a non-inverting operational amplifier ( $N_1$  in Fig. 4). It represents the hysteresis of the magnetization in the electrical circuit. An operational amplifier needs two supply voltages  $+V_{CC}$  and  $-V_{CC}$  (both are not shown in Fig. 4, but are assumed to be present). If the operational amplifier is operated in saturation mode, its output voltage is either  $-U_{SAT}$  if the input voltage is within the negative saturation range or  $+U_{SAT}$  if the input voltage is within the positive saturation range. The range of the input-voltage where the operational amplifier works linear depends on the device, whereas the voltages  $\pm U_{SAT}$  depend on the choice of  $\pm V_{CC}$ . The Schmitt-Trigger allows a hysteretic switching operation with two threshold voltages  $U_{IN,ON}$  and  $U_{IN,OFF}$  as shown in Figure 5. If the input voltage is greater or equal to  $U_{IN,ON}$ ,

the output voltage  $U_{HYS}$  is equal to the positive saturation voltage. If the input voltage is less than  $U_{IN,ON}$ ,  $U_{HYS}$  does not change. The output voltage does not change until the input voltage decreases to a value of  $U_{IN,OFF}$ . In this case the output voltage is equal to the negative saturation voltage. If the input voltage increases again,  $U_{HYS}$  does not change until the input voltage reaches  $U_{IN,ON}$ . With the resistors  $R_1$  and  $R_2$  the threshold-voltages can be chosen according to:

$$U_{HYS} = \begin{cases} -U_{SAT} \Rightarrow U_{IN,ON} = \frac{R_1}{R_2} U_{SAT} \\ +U_{SAT} \Rightarrow U_{IN,OFF} = -\frac{R_1}{R_2} U_{SAT} \end{cases} \quad (3)$$

Equation (3) describes the hysteresis of  $U_{HYS}$  as schematically shown in Fig. 5. The hysteresis can be tuned with the choice of  $\pm U_{SAT}$ ,  $U_{IN,ON}$  and  $U_{IN,OFF}$ ,  $R_1$  and  $R_2$  as Fig. 5 and Fig. 6 indicate.



**Figure 5.** Sketch of the hysteresis curve of the Schmitt-Trigger used in the circuit.  $U_{IN,OFF}$  denotes the input voltage, where output voltage switches from  $+U_{SAT}$  to  $-U_{SAT}$  (respectively  $U_{IN,ON}$ ).

### 3.2. Resistance switch

To switch between the parallel and the anti-parallel configuration an N-channel MOS transistor (enhancement type) is used as the load in a voltage divider. The load change depends on the resistance-change of the MOS-FET ( $M_1$  in Fig. 4). The resistance of the MOS-FET is high if the applied gate-voltage is less than the threshold-voltage required to establish a conductive channel between source-terminal and drain-terminal. The resistance is low if the appropriate gate voltage is applied (actual values depend on the used device). One can determine two cases:

- high resistance of the MOS or
- low resistance of the MOS.

The former case represents the case of an anti-parallel orientation of the magnetization of the free layer and the latter case represents the case of a parallel orientation. The circuit is expressed by the equations

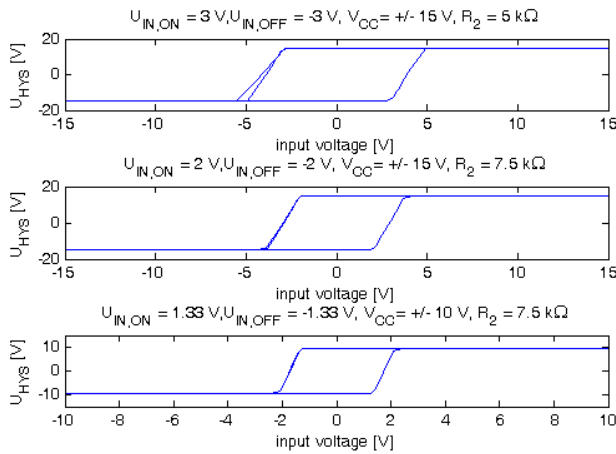
$$\frac{1}{R_P} = \frac{1}{R_5} + \frac{1}{R_{MOS,low} + R_4} \quad (4)$$

$$\frac{1}{R_{AP}} = \frac{1}{R_5} + \frac{1}{R_{MOS,high} + R_4}$$

where  $R_P$  represents the resistance of spin-valve in the case of a parallel orientation and  $R_{AP}$  represents the anti-parallel case.  $R_4$  and  $R_5$  are the resistors as sketched in Fig. 4.  $R_{MOS,high}$  represents the resistance of the MOS-FET when there is no conductive channel between source and drain terminal;  $R_{MOS,low}$  represents the resistance of the MOS-FET when the channel is established. As equation (4) shows, the resistance states of the MOS-FET play an important role. As a result one can determine between the two states by the resistance  $R_P$  and  $R_{AP}$ .

$$R_{MOS,low} < R_{MOS,high} \Leftrightarrow \frac{1}{R_{MOS,low}} > \frac{1}{R_{MOS,high}} \quad (5)$$

$$\Leftrightarrow \frac{1}{R_P} > \frac{1}{R_{AP}}$$



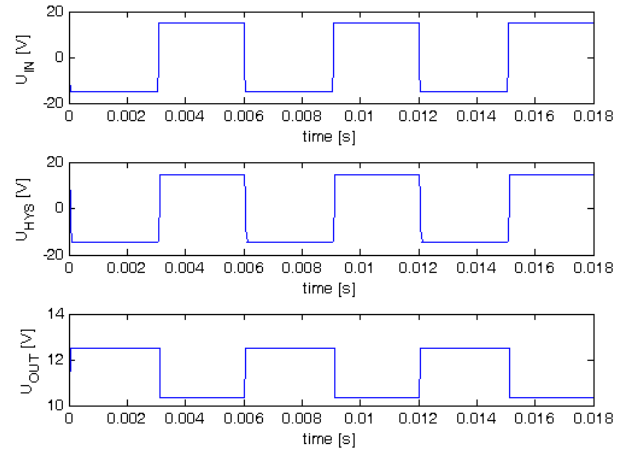
**Figure 6.** Comparison of hysteresis curves for different values of  $\pm U_{IN,OFF}$  and  $R_2$ , respectively. The rise and fall times are always 1ms. The basis of these plots is the signal shown in Fig. 8.

### 3.3. Simulation of the circuit

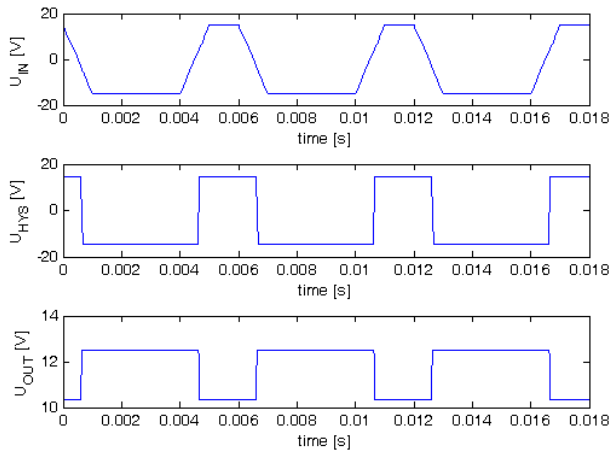
SPICE was developed at the University of California at Berkeley [10]. It is the de-facto standard simulator for electrical circuits. For the simulation the following parameters are used:

- The input voltage is a pulsed voltage with rectangular pulse form of alternating amplitudes between  $\pm 15$  V DC. The pulse-width is always 3ms since the operational amplifier we used can handle input-signals with frequencies less than 10 kHz as shown by the data-sheet [23]. The period-length is always 6 ms. It should be noted that this is a limitation of the current implementation of the electric circuit model. It does not represent the typical frequencies apparent in spin valve systems which are in the GHz-regime.
- The operational amplifier is a  $\mu A741$ . This type is a general purpose amplifier. The supply-voltages  $\pm 15$  V DC are used. Both offset-terminals of the  $\mu A741$  were grounded.
- The MOS-FET is the “MbreakN” model from PSPice’s “breakout” library.
- The resistors were  $R_1 = 1$  k $\Omega$ ,  $R_2 = 5$  k $\Omega$ ,  $R_3 = 5$  k $\Omega$ ,  $R_4 = 5$  k $\Omega$  and  $R_5 = 5$  k $\Omega$ .
- $V_{DC} = 25$  V DC

Figures 7 and 8 show the results of a transient analysis for different rise and fall times. The longer the rise and fall times are, the later the hysteresis voltages switches.



**Figure 7.** Simulation of the circuit with a rise time of  $50 \mu s$  and a fall time of  $50 \mu s$ .



**Figure 8.** Simulation of the circuit with a rise time of 1ms and a fall time of 1 ms.

#### 4. SUMMARY AND OUTLOOK

In this article we presented a hierarchical modeling and simulation scheme that constitutes an advancement in the design of and usability of spin valves in electric circuits. With the foundation of micromagnetic modeling and simulation we can extract parameters for SPICE modeling of the current-driven dynamic behavior of spin valves for use as non-volatile storage and even nanoscale programmable logical units (nPLUs). The approximation presented here will need to be refined, for instance hysteresis in the circuit. Once a realistic behavior is achieved, logical and arithmetical operations of spin valves as proposed in [8] can be simulated and evaluated. This is the basis for design of a field-programmable gate arrays based on spin valves.

#### 5. ACKNOWLEDGEMENTS

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#### References

- [1] [www.top500.org](http://www.top500.org)
- [2] Held, J.; Bautista, J; and Koehl, S. (editors). 2006. “From a Few Cores to Many: A Tera-scale Computing Research Overview”, White paper, Intel Corporation.
- [3] Gschwind, M; Hofstee, P. ; Flachs, B.; Hopkins, M. ; Watanabe, Y.; and Yamazaki, T. 2005. “A Novel SIMD Architecture for the Cell Heterogeneous Chip Multiprocessor”, *Hot Chips* **17**.
- [4] Burger D.; Keckler, S. W.; McKinley, K. S.; Dahlin, M.; John, L. K.; Lin, C.; Moore, C. R.; Burrill, J.; R. G. McDonald; W. Yoder, and the TRIPS Team. 2004. “Scaling to the End of Silicon with EDGE Architectures”, *Computer*, **37**, 44-55.
- [5] The International Technology Roadmap for Semiconductors. 2005. “Emerging Research Devices 2005 edition”.
- [6] R. Hartenstein. 2001. “A Decade of Reconfigurable Computing: A Visionary Retrospective,” *date*, 642, Design, Automation, and Test in Europe (DATE '01).
- [7] Freescale Semiconductor Inc. “Freescale’s award-winning MRAM achieves industrial and extended temperature qualification”, Press release. Online resource: <http://media.freescale.com/phoenix.zhtml?c=196520&p=irol-newsArticle&ID=1083398&highlight=> Last checked; 20 March 2008.
- [8] Ney, A.; C. Pampuch, R. Koch, and K. H. Ploog,. 2003. “Programmable computing with a single magnetoresistive element”, *Nature* **425**, 485-487.
- [9] Najafi, M.; B. Krüger; S. Bohlens; G. Selke; B. Güde; M. Bolte, and D.P.F. Möller. 2008. “The micromagnetic modeling and simulation kit M<sup>3</sup>S for the simulation of the dynamic response of ferromagnets to electric currents”. *Grand Challenges in Modeling & Simulation (GCMS'08)*.
- [10] Vladimirescu, A. 1994. *The SPICE book*. Wiley, New York, NY.
- [11] Stöhr, J.; H.C. Siegmann. 2006. *Magnetism – From Fundamentals to Nanoscale Dynamics*. Springer, Heidelberg, Germany.
- [12] Landau, L. and Lifshitz, E. 1935. “On the Theory of the Dispersion of Magnetic Permeability in Ferromagnetic Bodies”, *Physik. Z. Sowjetunion* **8**, 153.
- [13] Gilbert, T. L. 1955. “A Lagrangian Formulation of the Gyromagnetic Equation of Magnetization Field”, *Phys. Rev.* **100**, 1243.
- [14] Binasch, G.; P. Grünberg; F. Saurenbach, and W. Zinn. 1989. “Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange”, *Phys. Rev. B* **39**, 4828 – 4830.
- [15] Baibich, M. N.; J. M. Broto; A. Fert; F. Nguyen Van Dau; F. Petroff; P. Eitenne; G. Creuzet; A. Friederich, and J. Chazelas. 1988. “Giant Magnetoresistance of

- (001)Fe/(001)Cr Magnetic Superlattices”, Phys. Rev. Lett. **61**, 2472 – 2475.
- [16] Mott, N.F. 1964. Adv. Phys. **13**, 325.
- [17] Slonczewski, J. C. 2002. “Currents and torques in metallic magnetic multilayers”. Journ. Magn. Magn. Mat. **247**, 324–338.
- [18] Myers, E. B.; D. C. Ralph; J. A. Katine; R. N. Louie, and R. A. Buhrman. 1999. “Current-Induced Switching of Domains in Magnetic Multilayer Devices”. Science **285**, 867.
- [19] Donahue, M.J. and Porter, D.G. 1999. “Object oriented micromagnetic framework, OOMMF, User's Guide, Version 1.0”, Interagency Report NISTIR 6376, NIST, Gaithersburg, MD.
- [20] Chen Y.; X. Wang; H. Li; H. Liu, and D.V. Dimitrov. 2008. “Design Margin Exploration of Spin-Torque Transfer RAM (SPRAM)”. 9th International Symposium on Quality Electronic Design, 2008 (ISQED 2008) 684-690, 17-19 March 2008.
- [21] Zhao, W.; E. Belhaire; Q. Mistral; C. Chappert; V. Javerliac; B. Dieny, and E. Nicolle. 2006. “Macro-model of Spin-Transfer Torque based Magnetic Tunnel Junction device for hybrid Magnetic-CMOS design”. Proceedings of the 2006 IEEE International Behavioral Modeling and Simulation Workshop, 40-43, Sept. 2006.
- [22] Cadence Design Systems, Inc. 2008. “PSpice simulation”. Online resource: [http://www.cadence.com/products/orcad/pspice\\_a\\_d/index.aspx](http://www.cadence.com/products/orcad/pspice_a_d/index.aspx) Last checked: 25 May 2008.
- [23] Texas Instruments Incorporated. 2000. “ $\mu$ A741,  $\mu$ A741Y General-purpose operational amplifiers”. Datasheet.

## Biographies



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