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A device model framework for magnetoresistive sensors based on the Stoner–Wohlfarth model

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ABSTRACT

The Stoner–Wohlfarth (SW) model provides an efficient analytical model to describe the behavior of magnetic layers within magnetoresistive sensors. Combined with a proper description of magneto-resistivity an efficient device model can be derived, which is necessary for an optimal electric circuit design. Parameters of the model are determined by global optimization of an application specific cost function which contains measured resistances for different applied fields. Several application cases are examined and used for validation of the device model.

1. Introduction

Magnetic sensors offer the possibility of contact-less sensing and are used in a wide field of applications [1]. Read-head sensors for magnetic storage devices, magnetic bio-sensors and position-, speed- and binary-state sensors used in automotive- and industrial-applications are only a few examples. Compared with the well-established hall sensors, magnetoresistive sensors (xMR) offer higher sensitivity and thus allow a more flexible use of the sensors. Furthermore it is possible to combine the sensing element and signal conditioning electronics into one robust, monolithic design [2,3].

For an optimal design of the signal condition circuit a suitable device model of the sensing element is of utmost importance. Such a device model should contain all device features that are significant for a certain application case. On the other hand it should only be as complex as necessary, since the model needs to be very efficient. Furthermore, there should be a simple possibility to identify the model parameters of an individual sensor from corresponding measurement data.

While micromagnetic simulations with well-established tools [4] provide an accurate description of the magnetic state, those simulations are very time-consuming and it is difficult to directly interface them with electric circuit simulations. Device models based on electrical equivalent circuits [5,6] are well suited for integration in various hardware simulation environments like SPICE, VHDL-AMS or VERILOG-A. However using a modeling approach based on simplified physical assumptions is advantageous because it provides insight into the underlying physics and thus leads to more extensible models. In Ref. [7] a device model for a magnetic-tunnel-junction (MTJ) has been presented, which iteratively solves a Stoner–Wohlfarth (SW) model for a quasi-static description of the magnetic layers. Using the Landau–Lifshitz–Gilbert equation extends the model to dynamic magnetization processes [8,9].

Within this work an analytical solution of the Stoner–Wohlfarth model is used, providing an efficient and accurate description of the magnetic properties of the xMR sensor. In practice the subjective selection of optimal parameters for different models complicates the validation of model features. A generic and flexible method, based on the global optimization of an application specific cost function, is proposed to automatically determine

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reproducible optimal parameters for the model. The useability of the framework is demonstrated via different application cases.

The structure of the paper is as follows. Section 2 summarizes electric and magnetic properties of xMR sensors which will be described by the device model framework and explains in detail how the underlying Stoner-Wohlfarth model can be solved analytically. The solution of the global optimization problem introduced in Section 3 determines the optimal device parameters for a certain application case. Finally in Section 4 the device model is validated by comparison with measurements for several test cases.

2. Device model

xMR sensors consist of several thin magnetic layers which change their magnetization depending on the applied field, which in turn influences the resistance of the sensor. Although it is possible to directly measure the magnetic state of a magnetic layer (e.g. using the magneto-optic Kerr effect), it is more convenient to simply measure the total resistance of the device. Therefore it is necessary to model both the magnetic and the electric properties of the device.

2.1. Electric properties

Within this work the following types of magneto-resistance have been taken into account:

- *Anisotropic magnetoresistance (AMR):* AMR sensors only consist of a single magnetic layer which changes its resistance according to the angle ϕ_{AMR} between its magnetization and the applied electrical current. The AMR effect is a uniaxial effect, which can be described by the following relation [10]:

$$dR_{\mathrm{AMR}} = C_{\mathrm{AMR}} \cos^2(\phi_{\mathrm{AMR}}) \tag{1}$$

- *Giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR):* Both GMR [11] and TMR [12] sensors contain at least two magnetic layers. Within this work we are focusing on the so-called spin-valve sensors [13] which consist of a soft-magnetic free-layer and at least one pinned-layer. The magnetization of the free-layer is strongly influenced by the external field, whereas the pinned-layer determines a reference direction independent of the external field. The magnetization of the pinned-layer is fixed via exchange-coupling with an anti-ferromagnetic layer, which reduces the effective saturation magnetization M_s and thus increases the magnetic anisotropy field H_k. Pinning strength can be further improved by using two anti-ferromagnetically coupled pinned-layers. The GMR as well as the TMR effects show unidirectional behavior:

$$dR_{\mathrm{GMR}} = C_{\mathrm{GMR}} \cos(\phi_{\mathrm{GMR}}), \quad dR_{\mathrm{TMR}} = C_{\mathrm{TMR}} \cos(\phi_{\mathrm{TMR}}) \tag{2}$$

where ϕ_{GMR} and ϕ_{TMR} is the relative angle between the magnetizations within free- and pinned-layer. Despite the more complex structure of these sensors they are preferred for applications, because they provide larger sensitivities [1].

2.2. Magnetic properties

The Stoner–Wohlfarth (SW) model provides an analytical model to describe the magnetic layers as long as they behave like single-domain particles. This is the case especially for small sensors (<1 μm), but even for larger ones the SW model gives good approximations. Especially the use of proper biasing schemes, which are introduced to achieve linear output response, should prevent the occurrence of more complicated sensor states.

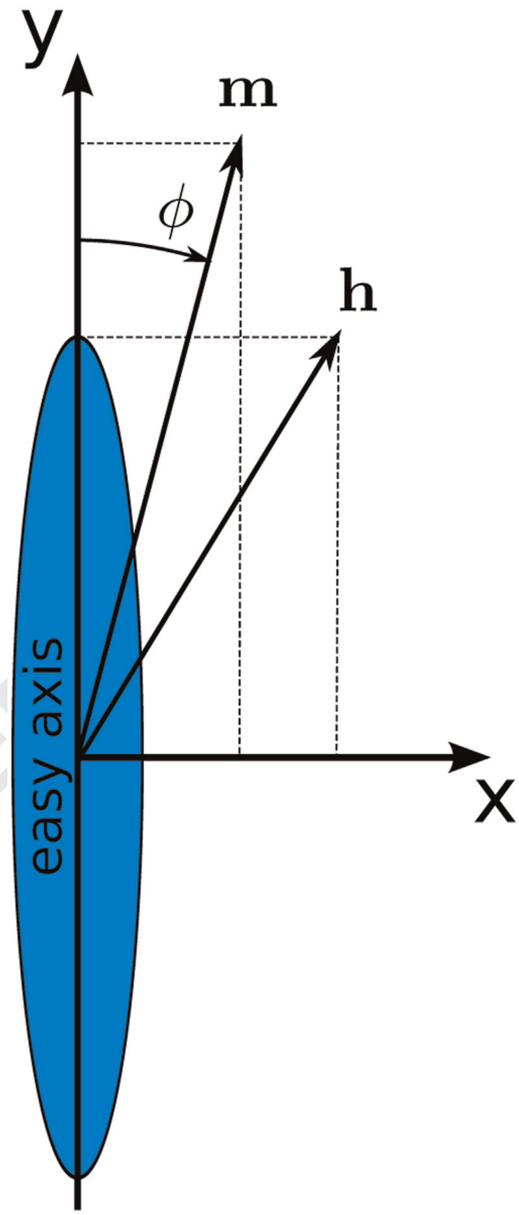

Fig. 1. Visualization of a Stoner–Wohlfarth particle with an uniaxial anisotropy along the y-axis (easy-axis). The applied field $\mathbf{h}$ leads to a magnetization $\mathbf{m}$ with a fixed modulus of M_s.

The SW model assumes a single-domain inside of a layer which allows us to describe the magnetization state as a single unit magnetization vector $\mathbf{m} = \mathbf{M}/M_s$. Only an external field and (uniaxial) anisotropy are considered. Due to the symmetry of the problem the magnetization lies within the plane spanned by the external field and the anisotropy axis, which reduces the problem to a 2D problem. The reduced total energy density reads as

$$\eta = \underbrace{\frac{1}{2}\sin^2(\phi)}_{\text{Anisotropy energy}} \underbrace{-h_x \sin(\phi) - h_y \cos(\phi)}_{\text{Zeeman energy}} \tag{3}$$

with $\eta = E/2KV$, $\mathbf{h} = \mathbf{H}/H_k$ and $H_k = 2K/\mu_0 M_s$. V is the volume of the layer, K the uniaxial anisotropy constant, μ_0 the permeability of the free space, and ϕ the angle between anisotropy easy-axis which is assumed along the y-axis (see Fig. 1). The stable magnetization states for an applied field can be calculated analytically, by a transformation to Cartesian coordinates as proposed in Ref. [14].