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Highly strain-sensitive magnetostrictive tunnel magnetoresistance junctions

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ABSTRACT

Tunnel magnetoresistance (TMR) junctions with CoFeB/MgO/CoFeB layers are promising for strain sensing applications due to their high TMR effect and magnetostrictive sense layer (CoFeB). TMR junctions available even in submicron dimensions can serve as strain sensors for microelectromechanical systems devices. Upon stress application, the magnetization configuration of such junctions changes due to the inverse magnetostriction effect resulting in strain-sensitive tunnel resistance. Here, strain sensitivity of round-shaped junctions with diameters of 11.3 μm, 19.2 μm, 30.5 μm, and 41.8 μm were investigated on macroscopic cantilevers using a four-point bending apparatus. This investigation mainly focuses on changes in hard-axis TMR loops caused by the stress-induced anisotropy. A macrospin model is proposed, supported by micromagnetic simulations, which describes the complete rotation of the sense layer magnetization within TMR loops of junctions, exposed to high stress. Below 0.2‰ tensile strain, a representative junction with 30.5 μm diameter exhibits a very large gauge factor of 2150. For such high gauge factor a bias field $H = -3.2$ kA/m is applied in an angle equal to $3\pi/2$ toward the pinned magnetization of the reference layer. The strain sensitivity strongly depends on the bias field. Applying stress along $\pi/4$ against the induced magnetocrystalline anisotropy, both compressive and tensile strain can be identified by a unique sensor. More importantly, a configuration with a gauge factor of 400 at zero bias field is developed which results in a straightforward and compact measuring setup.

1. Introduction

Strain sensing applications such as microcantilever technology, force sensors, and pressure sensors have widely benefited from piezoelectric [1] and piezoresistive [2] materials. Inspired by similar effects, recently extensive attempts on stretchable polymer thin films based on nanoscale structures [3–5] achieved higher strain sensitivity only for large deformations, aiming for high-strain sensing devices [6]. However concerning nano- and micro-scale strain measurements, high-speed read-out [7] and integrated devices demand higher strain sensitivity in the small strain range (below 0.2‰). Pursuing low-cost and miniaturized devices, the mechanism of magnetoresistance (MR) change in giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR) sensors via the inverse magnetostriction poses a promising approach for monitoring small mechanical quantities. The earliest GMR strain sensors [8–10] showed a gauge factor (*GF*) on the order of 150 in spite of further improvement by replacing NiFe with high magnetostrictive $Co_{50}Fe_{50}$ layer [11]. The significant enhancement of the strain sensitivity to the order of 300–600 has been achieved by TMR structures with crystalline $Co_{50}Fe_{50}$ [12] and amorphous $(Fe_{90}Co_{10})_{78}Si_{12}B_{10}$ [13] layers. Recently, employing CoFeB/MgO/CoFeB magnetic tunnel junctions (MTJs), which offer very large MR ratios up to 600% [14] as well as compatibility with mass-manufacturing techniques, resulted in a very large strain sensitivity up to 840 [15]. Interestingly, their high feasibility and durability has been demonstrated as pressure sensors [15] and self-sensing microcantilevers for atomic force microscopy (AFM) [16]. Note that all these strain sensors require an external bias magnetic field during operation, which is recognized as their technical drawback in terms of a simple and compact measuring setup.

The magnetostrictive TMR sensors are basically MTJs with a magnetostrictive sense layer which is free to rotate under mechanical strain/stress. Consequently, while the ferromagnetic reference layer is magnetically pinned, the magnetization configuration of the two layers alters upon stress. The resulting change of the tunnel resistance, due to its angular dependence $R(\alpha)$ in MTJs [17], can be quantitatively related to the applied stress. The

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stress-induced rotation of the sense layer magnetization has been investigated experimentally by optical Kerr effect measurements [18] and theoretically by the total energy minimization [12,19,20] for various configurations.

In this study, the magnetocrystalline anisotropy of the sense layer is aligned at $\pi/4$ angle toward the stress axis, which allows detection of both uniaxial stresses. TMR loops are first investigated under a variation of compressive and tensile mechanical strain [21]. A representative macrospin model provides details about the rotation of the sense layer magnetization of a strained junction in a TMR loop. Micromagnetic simulations are also performed in order to verify the behavior using the Object Oriented Micro-Magnetic Framework (OOMMF) [22]. The strain loops are measured at different bias fields leading to different gauge factors. Also, strain sensors are represented with high sensitivity at zero bias magnetic field.

2. Experimental

2.1. Sample fabrication

The MTJ multilayer structure was deposited on a Si/SiO$_2$ substrate by magnetron sputtering at a base pressure of 2×10^{-7} mbar. A Co$_{40}$Fe$_{40}$B$_{20}$ (3 nm) layer, known for high magnetostrictive coefficient [23], serves as the sense layer. The reference layer CoFeB with the same composition is magnetically stabilized via MnIr (12 nm)/CoFe (3 nm)/Ru (0.9 nm) layers, forming an exchange-biased artificial antiferromagnet [24]. Stabilization of the reference layer is carried out via field annealing at 360 °C in vacuum for 1 h under magnetic field of 159.2 kA/m. Furthermore, the field annealing causes crystallization of the CoFeB layers and improvement of the MgO/CoFeB interfaces [25]. Then, the TMR junctions were structured in round shapes by microelectromechanical systems (MEMS) methods. Their diameters range from 11.3 μm to 41.8 μm [16]. Finally, cantilevers with 3 mm × 25 mm dimension with TMR junctions patterned on top were diced so that the magnetization of the sense layer (uniaxial magnetocrystalline anisotropy K_u), induced during field annealing process, is aligned at $\pi/4$ toward the long side of the cantilevers or the axis of applied stress.

2.2. Characterization of magnetostrictive TMR sensors

The performance of the magnetostrictive TMR sensors on cantilevers was characterized by a four-point bending apparatus [12]. The TMR loops (resistance vs. magnetic field) were characterized first without uniaxial stress in the cantilever and then while maintaining constantly different uniaxial stress magnitudes. The magnetic field was swept perpendicular to the induced easy axis of the sense layer (along so-called hard axis) while the tunnel resistance of the wire-bonded sensors was simultaneously recorded under 10 mV voltage by a Keithley 2400 source meter. This allows to understand the rotation mechanism of the sense layer magnetization and to detect at which bias magnetic field a maximum resistance change occurs for a certain change of strain.

Moreover, strain loops as resistance vs. strain were measured at various bias fields to estimate the gauge factors for every sensors with different sizes. The gauge factor is defined by averaging the ratios of relative change of resistance to 0.2‰ strain in forward and backward pathways of strain.

2.3. Micromagnetic model simulations

The simulations were carried out using OOMMF [22], by minimizing the total free energy of the magnetic system, numerically solving the Landau–Lifshitz equation. The total magnetic energy consists of the exchange energy, demagnetizing energy originating from the stray field, induced uniaxial anisotropy imposed by the field annealing (K_u), Zeeman energy generated by an externally applied field and finally magnetoelastic energy, in this case stemming from external stress (K_σ). K_u was calculated from the relation $K_u = \mu_0 H_k M_s/2$ where H_k is the magnetic anisotropy field determined from fitting the hard-axis hysteresis curves (not shown here). For small strains, the magnetoelastic energy is assumed in terms of an uniaxial anisotropy which is scaling with the applied strain ε and given by $K_\sigma = \frac{3}{2}\lambda_s \sigma$ with $\sigma = Y\varepsilon$ and λ_s being the isotropic saturation magnetostriction and $Y = 200$ GPa the Young's modulus [12].

Table 1
The material parameters used for the micromagnetic simulations.

Physical quantity	Value
Saturation magnetization (M_s)	1030 kA/m
Induced anisotropy (K_u)	3860 J/m^3
Isotropic magnetostriction (λ_s)	30×10^{-6} [28]
Exchange stiffness (A)	6.5×10^{-12} J/m [29]

The simulation volume consists of a mono-layer of cubic discretization cells, having an edge length of 5 nm. This is on the order of the exchange length of CoFeB [26], giving a compromise between accuracy and computation time. For simplicity only the sense layer of a round junction with diameter of 11.3 μm is taken into account. The simulation parameters are summarized in Table 1.

Lateral junction dimensions were taken from bitmap files and a randomizing algorithm was used in order to introduce an edge roughness of up to 30 nm, which is of the same order as previous reports using magnetic force microscopy images [27].

The induced magnetocrystalline anisotropy is modeled using a textured vector field, having its principal axis parallel to the applied magnetic field during the field annealing. The parallel and antiparallel resistance R_p and R_{ap} respectively, as well as the perpendicular resistance $R_\perp$ were determined experimentally. Using the equation published by Jaffrès et al. [17], the calculation of the resulting junction resistance $R(\alpha)$ was done with the MATLAB® software, as the simulation cells of the sense layer are assumed to be parallel conduction channels as published recently [30]. For each cell, the magnetization angle with respect to the reference layer fixed magnetization was calculated by iterating over magnetization vector field files.

3. Results and discussion

3.1. Strain effects on hard-axis TMR loop

Fig. 1 shows the successive changes of measured TMR loops ($R(H)$) imposed by different uniaxial tensile and compressive strain. For simplicity, the result of a round junction (diameter = 11.3 μm) without in-plane shape anisotropy is demonstrated. The junction has 198% TMR amplitude and 496 kΩ μm^2 resistance-area product (RA). In the loop of the junction under no stress (solid blue line, see Fig. 1), an external magnetic field H is applied perpendicular to the induced magnetocrystalline anisotropy of the sense layer, what we call a hard-axis TMR loop in this context. A schematic of the configuration is shown in Fig. 1(a). Here, a negative sign of the magnetic field corresponds to an angle equal to $3\pi/2$ toward the pinned