Vol 18 No 6, June 2009
1674-1056/2009/18(06)/2589-07

Chinese Physics B

© 2009 Chin. Phys. Soc.
and IOP Publishing Ltd

# The magnetoresistive effect induced by stress in spin-valve structures*

Qian Li-Jie(钱丽洁), Xu Xiao-Yong(许小勇), and Hu Jing-Guo(胡经国)†

*College of Physics Science and Technology, Yangzhou University, Yangzhou* 225002, *China*

(Received 5 October 2008; revised manuscript received 10 December 2008)

Using a method of free energy minimization, this paper investigates the magnetization properties of a ferromagnetic (FM) monolayer and an FM/antiferromagnetic (AFM) bilayer under a stress field, respectively. It then investigates the magnetoresistance (MR) of the spin-valve structure, which is built by an FM monolayer and an FM/AFM bilayer, and its dependence upon the applied stress field. The results show that under the stress field, the magnetization properties of the FM monolayer is obviously different from that of the FM/AFM bilayer, since the coupled AFM layer can obviously block the magnetization of the FM layer. This phenomenon makes the MR of the spin-valve structure become obvious. In detail, there are two behaviors for the MR of the spin-valve structure dependence upon the stress field distinguished by the coupling (FM coupling or AFM coupling) between the FM layer and the FM/AFM bilayer. Either behavior of the MR of the spin-valve structure depends on the stress field including its value and orientation. Based on these investigations, a perfect mechanical sensor at the nano-scale is suggested to be devised experimentally.

**Keywords:** magnetization, magnetoresistance, spin-valve structure, stress field
**PACC:** 7570, 7580, 7570K, 7540M

## 1. Introduction

Giant magnetoresistance (GMR), which was first discovered in Fe/Cr multilayers by Baibich *et al*[1−5] in 1988, has attracted much attention due to its crucial role in magnetic sensor and information storage technology. The virtue of the spin-valve structure is that only a weak magnetic field can achieve the variety of the magnetic orders between the adjacent magnetic layers and make obvious magnetoresistance.

In 1991, Dieny *et al* made the $Ni_{81}Fe_{19}/Cu/Ni_{80}Co_{20}/Fe_{50}Mn_{50}$ system[6] called a spin-valve system and obtained the magnetization and MR curves under CIP geometry, they found that its MR can reach 5%. This related phenomenon has been studied extensively in magnetic multilayers, and now this effect has been applied successfully in digital storage and magnetic sensor technology. More recently, however, ferroelectric materials have attracted more attention, because electromagnetic coupling can be applied to control the spin state of the electron using an electric field and to produce the GMR effect. On the other hand, the storage, read-writing and transmission of the mechanical signals widely exist in practical applications, and research on GMR induced by mechanics is still scarce. Hence it is necessary to study the magneto-resistive effect of the spin-valve structure induced by stress. Experiments[7,8] have shown that the strain transferred by applying magnetic field to the thin film prepared on a wafer or a substrate can approach 2% and the corresponding order of magnitude is MPa. Recently, Saranu *et al*[8] have built a Co/Cu/Ni PSV system to discuss the effect of uniaxial stress on the magnetic properties of thin films and GMR sensors prepared on polyimid substrates. They concluded that the sensitivity and the operating range of the GMR sensor can both be optimized by the applied stress.

This article is organized as follows. Section 2 is devoted to the basic model and the total equilibrium energies for an FM monolayer and an FM/AFM bilayer, respectively. The MR of the spin-valve structure under applied stress fields is also derived in Section 2. The relevant numerical analyses and discussion are presented in Section 3. Finally a brief summary is given in Section 4.

## 2. The model and formulation

In the calculation, we firstly discuss the magnetization behaviors of an FM monolayer and an

*Project supported by the National Natural Science Foundation of China (Grant No 10347118) and Natural Science Foundation of College of Jiangsu Province, China (Grant Nos 2006KJB140133 and 2007KJD140241).
†Corresponding author. E-mail: jghu@yzu.edu.cn hujgyz@263.net

FM/AFM bilayer under a stress field, respectively. Then we analyse and discuss the characteristics of the MR of a typical spin-valve structure composed of an FM monolayer and an FM/AFM bilayer.

## 2.1. FM monolayer

We assume that the FM monolayer film with uniaxial magnetocrystalline anisotropy[9] is taken to lie in the $x$–$y$ plane with the $z$ axis normal to the layer plane. In spherical coordinates, we use $\theta$ and $\varphi$ as the polar angle for the $z$ axis and azimuthal angle for the $x$ axis, respectively. A stress $\sigma$ is applied in the $x$–$y$ plane and makes an angle $\varphi$ with the $x$ axis. The total energy per unit area for the FM monolayer can be written as:

$$E = -\frac{3}{2}\lambda\sigma\cos^2(\varphi-\phi) + K_{\rm uef}t_{\rm F}\sin^2\theta + K_{\rm up}t_{\rm F}\sin^2\theta\sin^2\phi. \quad (1)$$

Here the first term is the energy of the stress field.[10,11] The second term is the uniaxial magnetocrystalline anisotropy energy with an effective anisotropy constant $K_{\rm uef}$ which is defined as $K_{\rm u} - 2\pi M^2$, where $K_{\rm u}$ is the uniaxial magnetocrystalline anisotropy constant. The third term represents the in-plane uniaxial magnetocrystalline anisotropy energy with a constant $K_{\rm up}$.

At equilibrium, the first derivative of $E$ with respect to $\theta$ and $\varphi$ must be equal to zero. A trivial solution of the equilibrium equation is $\theta = \pi/2$. This means that the saturated magnetization $M$ of the FM monolayer must lie in the layer plane. The angles $\varphi$ and $\phi$ will be determined from the following equation:

$$\frac{3}{2}H_\lambda\sin 2(\varphi-\phi) - \frac{1}{2}H_A\sin 2\phi = 0. \quad (2)$$

Where $H_\lambda = \dfrac{\lambda\sigma}{Mt_{\rm F}}$ and $H_A = \dfrac{2K_{\rm up}}{M}$ are called the stress field and the uniaxial anisotropic field, respectively.

## 2.2. FM/AFM bilayer

The FM layer is considered to be a cubic single crystal whose thickness is $t_{\rm F}$, but only the uniaxial magnetocrystalline anisotropy is taken into account, and similarly for the AFM layer. However the thickness of AFM layer $t_{\rm AF}$ is assumed to be sufficiently large such that it can be regarded as semi-infinite.

We assume a perfect uncompensated interface[12] between the FM layer and the AFM layer. The bilayer is taken to lie in the $x$–$y$ plane with the $z$ axis normal to the layer plane. An angle $\alpha$ is defined between the AFM magnetization and the $x$ axis in the interface, it is determined by the total magnetization of the FM/AFM bilayer at equilibrium. So we call the angle $\alpha$ the pinning angle, which indicates the pinning strength of the AFM layer coupled with the FM layer. In spherical coordinates, we use $\theta$ and $\phi$ as the polar angle for the $z$ axis and the azimuthal angle for the $x$ axis, respectively. A stress $\sigma$ is applied in the $x$–$y$ plane and makes an angle $\varphi$ with the $x$ axis. The total energy per unit area for the FM/AFM bilayer[12] can be written as:

$$E = -\frac{3}{2}\lambda\sigma\cos^2(\varphi-\phi) + 2\sqrt{A_{\rm AF}K_{\rm AF}}(1-\cos\alpha) - J_1\sin\theta\cos(\alpha-\phi) + K_{\rm uef}t_{\rm F}\sin^2\theta + K_{\rm up}t_{\rm F}\sin^2\theta\sin^2\phi. \quad (3)$$

Here the second term is the volume energy of the AFM layer with $\varepsilon_{\rm AFM} = 2\sqrt{A_{\rm AF}K_{\rm AF}}$ the domain wall energy of the AFM layer. The third term is the exchange-coupling energy at the interface between the FM and AFM layer where $J_1$ is the exchange coupling constant which results in the exchange bias.

At equilibrium, the free energy is at a minimum, so we find that $\theta = \pi/2$ is still one solution of the equation which means the saturated magnetization $M$ of the FM layer lies in the layer plane. The relation between $\varphi$ and $\phi$ is represented by the following expression

$$\frac{3}{2}H_\lambda\sin 2(\varphi-\phi) - \frac{1}{2}H_A\sin 2\phi - \frac{H_{\rm E}\sin\phi}{\sqrt{1+2g\cos\phi+g^2}} = 0, \quad (4)$$

where $H_\lambda = \dfrac{\lambda\sigma}{Mt_{\rm F}}$, $H_A = \dfrac{2K_{\rm up}}{M}$, $H_E = \dfrac{J_1}{Mt_{\rm F}}$ and $g = \dfrac{J_1}{2\sqrt{A_{\rm AF}K_{\rm AF}}}$ are called respectively the stress field, the uniaxial anisotropic field, the exchange coupling field and the interfacial 'turning' coefficient which indicates the 'pinning' effect of the AFM layer on the magnetization of the FM layer.

## 2.3. Spin-valve structure

Spin-valve structure[12] consists of an FM monolayer and an FM/AFM bilayer separated by a nonmagnetic layer. For simplicity, we assume that the coupling between the two FM layers is so weak that it can be neglected. We define $\phi_s$ and $\phi_d$ as the magnetizations of the FM monolayer and the FM/AFM bilayer, respectively. According to Eqs.(2) and (4),

we obtain the dependence of $\phi_s$, $\phi_d$ and $\Delta\phi = \phi_s - \phi_d$ upon the value and orientation of the stress field. Both theory and experiments[13,14] show that, for the perfect situation the relation between the MR of the spin-valve structure and the magnetization difference $\Delta\phi$ can be expressed as follows:

$$R(\Delta\phi) = R^P + \Delta R \sin^2(\Delta\phi/2), \quad \text{for} \quad J > 0, \tag{5}$$

$$R(\Delta\phi) = R^A - \Delta R \cos^2(\Delta\phi/2), \quad \text{for} \quad J < 0. \tag{6}$$

Hence, the corresponding reluctivity is

$$\mathrm{MR} \equiv \frac{R(\Delta\phi) - R^P}{R^P} = \frac{\Delta R}{R^P} \sin^2(\Delta\phi/2), \tag{7}$$

or

$$\mathrm{MR} \equiv \frac{R(\Delta\phi) - R^A}{R^P} = -\frac{\Delta R}{R^A} \cos^2(\Delta\phi/2). \tag{8}$$

Here $R^P$ is the resistance when the magnetizations of the two FM layers are parallel while $R^A$ is the antiparallel resistance, $\Delta R$ is the maximum MR as $\Delta R = R^A - R^P$, $R(\Delta\phi)$ denotes the resistance when the relative orientation of the magnetizations between the adjacent layers is $\Delta\phi$. Based upon Eqs.(2), (4), (7) and (8), the stress dependences of MR of the spin valve structure can be discussed in detail.

## 3. Analysis and discussion

From Eqs.(2) and (4), we can obtain the magnetization of the FM monolayer and FM/AFM bilayer and their difference, and find that this difference depends on the stress including its magnitude and orientation, the exchange coupling and the magnetocrystalline anisotropy. There are two cases in which parallel and antiparallel arrays for the easy axes of the two FM layers correspond to FM coupling and AFM coupling, respectively. For simplicity, we assume that the easy axis of the FM/AFM bilayer is aligned along the $x$ axis during the discussion while the easy axis of the FM monolayer can be rotated freely. Meanwhile only the uniaxial magnetocrystalline anisotropy is considered for the FM layer. The parameters used for the fitting are given as:[13] $4\pi M = 10$ MA/m, $H_{\mathrm{A1}} = H_{\mathrm{A2}} = 1.0$ MA/m, $H_{\mathrm{E}} = 1.0$ MA/m, $g = 0.5$.

Firstly, let us discuss the case of FM exchange-coupling. For magnetization orientations $\phi$ of the FM monolayer and FM/AFM bilayer, magnetization difference $\Delta\phi$ and MR of the spin-valve structure vs. stress direction $\varphi$, we find that there are two behaviors called strong and weak stress fields, respectively. As can be seen in Fig.1(a), under weak stress field the behavior of the dependence of the magnetizations $\varphi$ of the FM monolayer and FM/AFM bilayer with orientation $\phi$ of the stress field can be described by a sinusoid-like curve, but the MR of the spin-valve structure can be approximately pictured by a squared sinusoid with $\mathrm{MR}_{\max} \approx 0.007\Delta R/R^P$. On the other hand, the

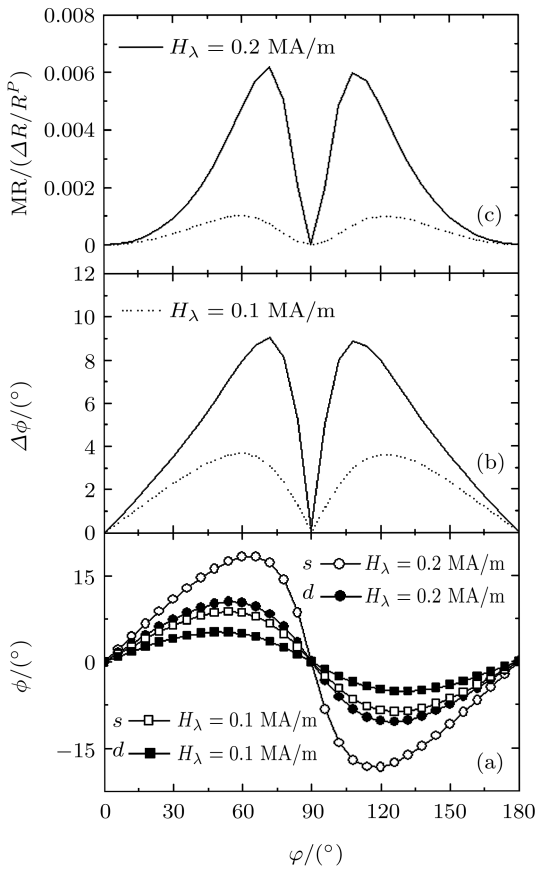



**Fig.1.** Magnetization orientations $\phi$ of the FM monolayer and FM/AFM bilayer, magnetization difference $\Delta\phi$ and magnetoresistance (MR) of the spin-valve structure vs. the weak stress direction $\varphi$ for FM coupling.

behavior is symmetric for $\phi = \pi$ due to the fact that the dependence of the stress field energy on orientation $\phi$ of the stress field is uniaxial. Namely, magnetization induced by a stress field along or against the orientation $\phi$ of the stress field is equivalent. But the magnetization induced by a stress field in the FM monolayer is obvious from that of the FM/AFM bilayer as shown in Fig.1(b), because of the pinning of the AFM layer,[15] so the AFM layer coupling protects against variation of the magnetization of the FM layer.[16] In detail, the dependence of the magnetization difference $\Delta\phi = \phi_s - \phi_d$ upon $\phi$ is non-monotonic, its maximum appears near $\varphi = 90°$, and the critical angle of the stress field corresponding to the maximum mag-

netization change will approach $\varphi = 90°$ with the increase of the stress field $H_\lambda$. However when the stress field further increases, i.e. in the strong field case, the behavior of the dependence of magnetization upon orientation $\phi$ will be changed as shown in Fig.2.

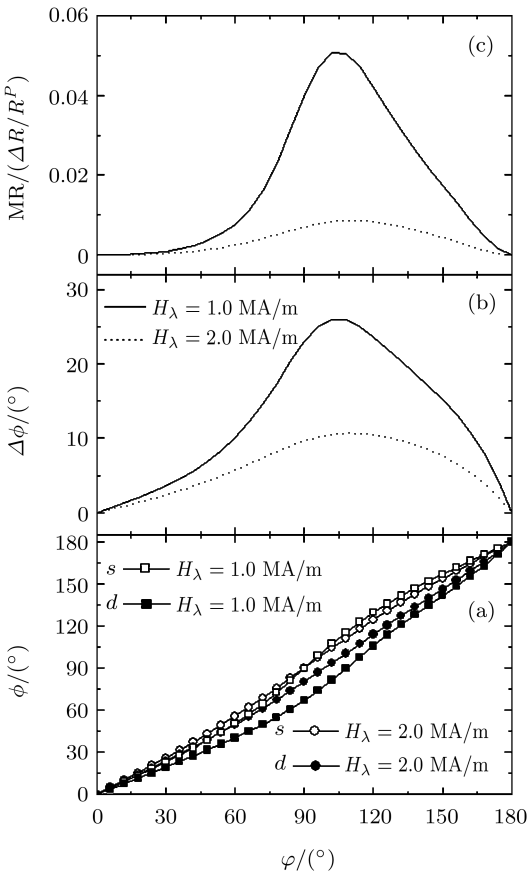



**Fig.2.** Magnetization orientations $\phi$ of the FM monolayer and FM/AFM bilayer, magnetization difference $\Delta\phi$ and MR of the spin-valve structure vs. the strong stress direction $\varphi$ for FM coupling.

In the strong field regime, the magnetizations $\phi$ of the FM monolayer and FM/AFM bilayer both increase approximately linearly with the increase of $\varphi$, but the magnetization induced by the stress field in the FM monolayer is also obviously faster than that of FM/AFM bilayer as shown in Fig.2(a) because of the pinning of the AFM layer. The corresponding magnetization difference $\Delta\phi$ vs. the stress field angle $\varphi$ is shown in Fig.2(b). From Fig.2(b), we find that $\Delta\phi$ also non-monotonically increases with the increase of $\varphi$, and $\Delta\phi$ increases markedly for larger stress field. The MR dependence upon $\varphi$ is similar to the $\Delta\phi$ dependence as shown in Fig.2(c). On the whole, the MR dependence upon $\varphi$ in the strong stress field is more obvious than that in the weak stress field, and the maxium of MR can approach $\mathrm{MR_{max}} \approx 0.051\Delta R/R^P$. This is beneficial for one application of mechanical sensors, which is based on the MR induced by $\varphi$.

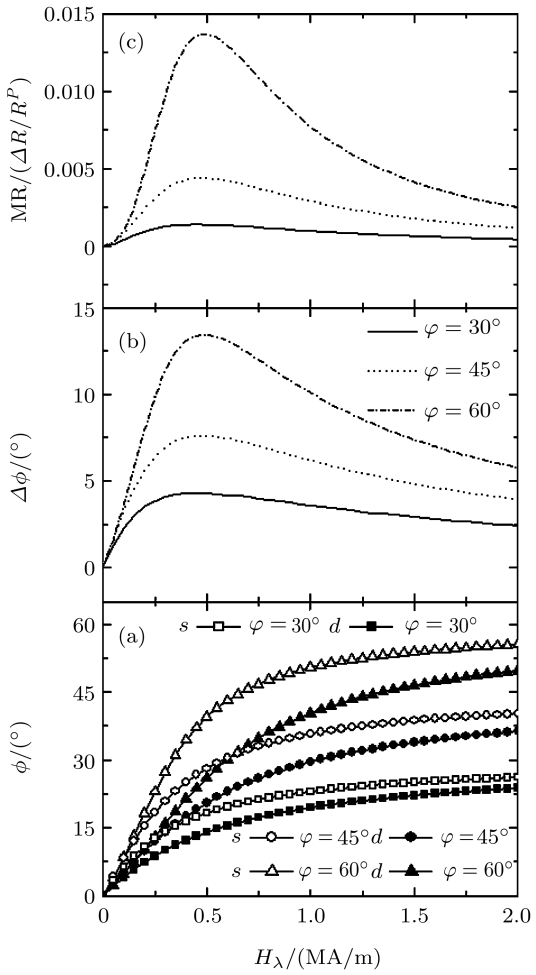



**Fig.3.** Magnetization orientations $\phi$ of the FM monolayer and FM/AFM bilayer, magnetization difference $\Delta\phi$ and MR of the spin-valve structure vs. the magnitude of the applied stress field $H_\lambda$ under different stress field angles for FM coupling.

In Fig.3(a), we find that both magnetizations $\phi$ of the FM monolayer and FM/AFM bilayer monotonically increase with the increase of $H_\lambda$, but the difference between the magnetizations $\Delta\phi$ first increases quickly then gradually saturates. The dependence of MR upon stress field $H_\lambda$ is characterized in Fig.3(c), we find that MR/($\Delta R/R^P$) will reach the maximum under little stress field then decrease, finally approaching a constant. Moreover, the phenomena are obvious for larger stress field angles. When $H_\lambda = 0.5$ MA/m, for example, $\mathrm{MR_{max}} \approx 0.0048\Delta R/R^P$ at $\varphi = 45°$, yet $\mathrm{MR_{max}} \approx 0.0142\Delta R/R^P$ at $\varphi = 60°$. This means that the MR of the spin-valve structure is more sensitive to the stress field $H_\lambda$ under large $\varphi$.

Similarly, for the case that the easy axes of the two FM layers are antiparallel (AFM coupling), the

magnetization and MR behavior of the spin-valve structure can also be discussed. The results are shown in Figs.4, 5 and 6.

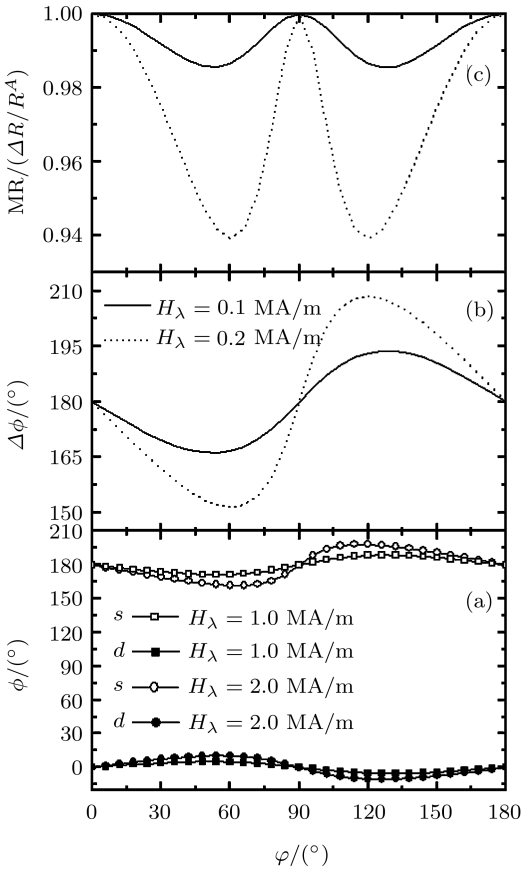



**Fig.4.** Magnetization orientations $\phi$ of the FM monolayer and FM/AFM bilayer, magnetization difference $\Delta\phi$ and MR of the spin-valve structure vs. the weak applied stress field angle $\phi$ for AFM coupling.

As can be seen in Fig.4(a), under weak stress field the dependence of magnetizations $\phi_s$ of the FM monolayer and $\phi_d$ of the FM/AFM bilayer on stress field angle $\phi$ still can be described by a sinusoid-like curve as in Fig.1(a), but the $\phi_s$ of the FM monolayer rotates with $\phi = 180°$ as the equilibrium axis while $\phi_d$ of the FM/AFM bilayer rotates with $\phi = 0°$ as the equilibrium axis, and their variations are contrary due to AFM coupling. In particular, the dependence of differences of magnetizations $\Delta\phi$ upon $\phi$ can also be described by a sinusoid-like curve as shown in Fig.4(b). However the dependence of the MR of the spin-valve structure upon $\phi$ is similar to that of FM coupling, but their changes go contrarily as shown in Figs.1(c) and 4(c).

In the strong stress field regime, the magnetizations $\phi_s$ and $\phi_d$ both linearly increase with the increase of $\varphi$, but $\phi_s$ decreases while $\phi_d$ increases due to AFM coupling in comparison with the case of FM coupling as shown in Figs.5(a) and 2(a). However, $\Delta\phi$ and MR vs. $\varphi$ are both non-monotonic, which is similar to the case of FM coupling. The maximum change of $\Delta\phi$ and MR occurs near $\varphi = 90°$, but the changes are opposite to the case of FM coupling as shown in Figs.5(b), 5(c) and 2(b), 2(c). However, the maximum MR can approach $\mathrm{MR}_{\max} \approx 0.92\Delta R/R^A$. In addition, the variations of $\Delta\phi$ and MR vs. stress field $H_\lambda$ become slow in comparson with the case of FM coupling.

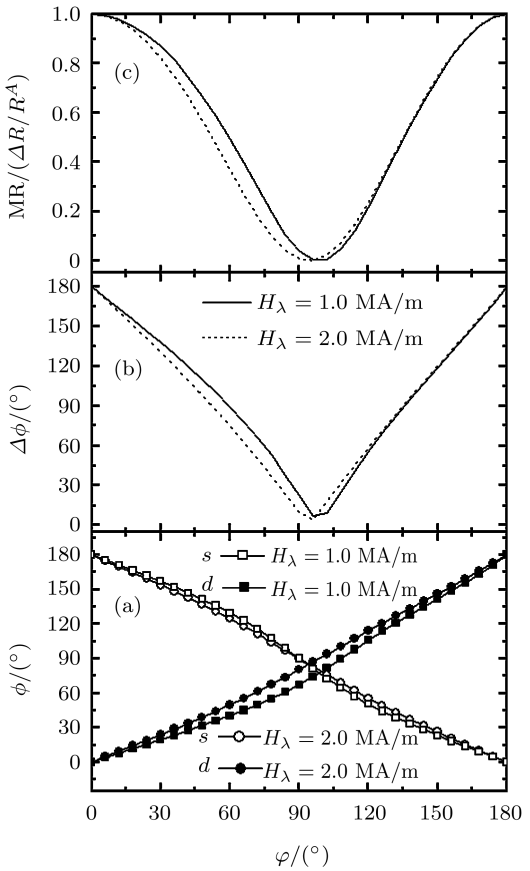



**Fig.5.** Magnetization orientations $\phi$ of the FM monolayer and FM/AFM bilayer, magnetization difference $\Delta\phi$ and MR of the spin-valve structure vs. the strong applied stress field angle $\phi$ for AFM coupling.

From Fig.6(a), we can find that magnetization orientations $\phi_s$ of the FM monolayer and magnetization orientations $\phi_d$ of the FM/AFM bilayer both approach the orientation of the stress field with increasing $H_\lambda$ then reach the saturation. Magnetization differences $\Delta\phi$ and magnetoresistance $\mathrm{MR}/(\Delta R/R^P)$ both decrease then approach saturation with increasing stress field $H_\lambda$ as shown in Figs.6(b) and 6(c), respectively.

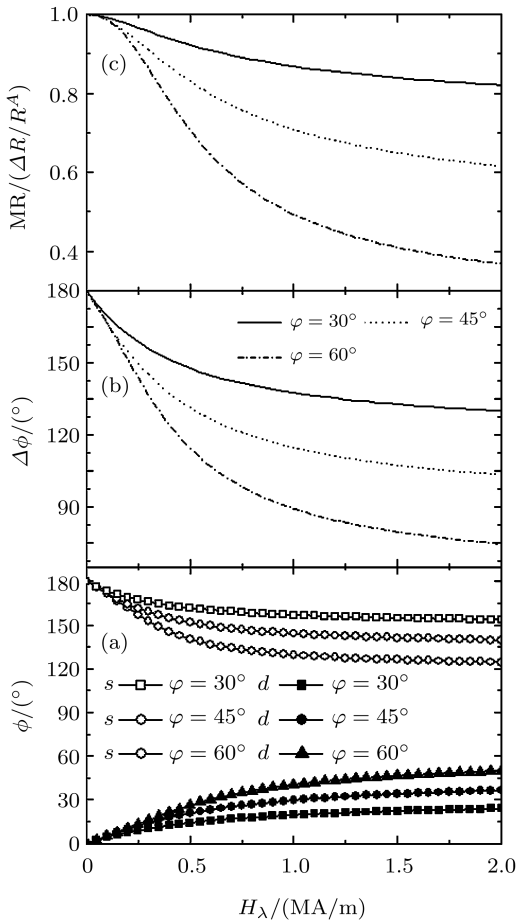



**Fig.6.** Magnetization orientations $\phi$ of the FM monolayer and FM/AFM bilayer, magnetization difference $\Delta\phi$ and MR of the spin-valve structure vs. the applied stress field $H_\lambda$ for AFM coupling.

# 4. Conclusion

Based on free energy minimization of the system, we have investigated the magnetization properties of an FM monolayer and an FM/AFM bilayer induced by the stress field, respectively. And then for MR of the typical spin-valve structure, which consists of an FM layer and an FM/AFM bilayer separated by a nonmagnetic layer, its dependence upon the applied stress field has been studied. The results show that under the stress field, the magnetization properties of the FM monolayer are obviously different from those of the FM/AFM bilayer, since the coupled AFM layer would obviously counteract the magnetization of the FM layer. This phenomenon which results in MR of the spin-valve structure becomes obvious. In detail, there are two behaviors for the dependence of the MR of the spin-valve structure upon the stress field distinguished by the coupling (FM coupling or AFM coupling) between the FM layer and FM/AFM bilayer. Either behavior of MR of the spin-valve structure depends on the stress field including its value and orientation. For FM coupling, namely in this case the magnetization of the FM layer is parallel to that of the FM/AFM bilayer for the initial state without stress field. We find that there are two behaviors for the magnetization and MR dependence of the stress field, which are determined by the magnitude of the stress field. In the weak stress field regime, the magnetization and MR dependence of the orientation of the stress field $\phi$ can be approximately pictured by a sinusoid and its square of $\phi$, respectively, but its period is $\pi$ because of the uniaxiality of the magnetization induced by the stress field. In the strong stress field regime, the magnetization almost approaches the orientation of the stress field while the MR of the spin-valve structure is non-monotonic with orientation of the increasing stress field. For a given orientation of the stress field, the magnetization always approaches the orientation of the stress field with increasing stress field, however the MR of the spin-valve structure first increases then decreases with increasing stress field. On the other hand, for AFM coupling, in this case the magnetization of the FM layer and FM/AFM bilayer are antiparallel without stress field, the results show that the magnetization properties of the FM monolayer and FM/AFM bilayer induced by the stress field and the dependence of the MR of the typical spin-valve structure upon the stress field are similar to those for FM coupling but their variation almost inverses with increasing stress field including its magnitude and angle. Based on these investigations, we will devise experimentally the perfect mechanical sensor at the nano-scale.

# References

[1] Hinchey L L and Mills D L 1986 *Phys. Rev.* B **33** 3329

[2] Grünberg P, Schreiber R, Pang Y, Brodsky M B and Sowers H 1986 *Phys. Rev. Lett.* **57** 2442

[3] Carbone C and Alvarado S F 1987 *Phys. Rev.* B **36** 2433

[4] Baibich M N, Broto J M, Fert A, Nguyen Van Dau F, Petroff F, Eitenne P, Creuzet G, Friederich A and Chazelas J 1988 *Phys. Rev. Lett.* **61** 2472

[5] Binasch G, Grünberg P, Saurenbach F and Zinn W 1989

*Phys. Rev.* B **39** 4828
[6] Dieny B 1994 *J. Magn. Magn. Mater.* **136** 335
[7] Ciria M, Arnaudas J I, Moral A del and O'Handley RC 2004 *Phys. Rev.* B **70** 054431
[8] Özkaya B, Saranu S, Mohanan S and Herr U 2008 *Phys. Stat. Sol.* (a) **205** 1876
[9] Layadi A, Ciarallo F and Artman J 1987 *IEEE Trans. Magn.* **23** 3642
[10] Miao C, Xiao C and Cupta A 2005 *Phys. Rev.* B **71** 094418
[11] Pan J and Hu J G 2006 *Phys. Lett.* A **358** 236
Hu J G and Stamps R L 2006 *Chin. Phys.* **15** 1595
[12] Thanh N T, Chun M G, Schmalhorst J, Reiss G, Kim K Y and Kim C G 2006 *J. Magn. Magn. Mater.* **304** e84
[13] Pan J, Tao Y C and Hu J G 2006 *Acta Phys. Sin.* **55** 3032 (in Chinese)
[14] Barnas J, Baksalary O and Fert A 1997 *Phys. Rev.* B **56** 6079
[15] Zhou S M, Li H Y, Yuan S J and Wang L 2003 *Prog. Phys.* **23** 62 (in Chinese)
[16] Hu J G, Jin G J and Ma Y Q 2002 *J. Appl. Phys.* **91** 2180