第 17 卷 第 6 期
2009 年 6 月

光学 精密工程
Optics and Precision Engineering

Vol. 17 No. 6
Jun. 2009

文章编号 1004-924X(2009)06-1322-05

利用退火方法降低自旋阀薄膜的矫顽力

李 伟[1,2],刘华瑞[3],任天令[3],刘理天[3]

(1.重庆大学 光电技术与系统教育部重点实验室,重庆 400044;
2.重庆大学 微系统研究中心,重庆 400044;3.清华大学 微电子学研究所,北京 100084)

摘要:降低自旋阀薄膜矫顽力对于制作巨磁电阻(GMR)传感器非常重要。报告了利用退火方法降低自旋阀薄膜矫顽力的实验结果,介绍了数值模拟退火的条件和方法,借助计算机对退火实验的条件及其实验结果进行了模拟。结果表明,模拟后的结果可以用来进一步优化退火条件,并不再需要做大量退火实验。使用优化后的退火条件大大降低了自旋阀薄膜的矫顽力同时可保持自旋阀的磁电阻变化率(*MR*)在较高的水平。介绍了不同退火参数下的模拟实验,结果显示退火前样品的的矫顽力为 358.2 A/m、MR 为 9.24%,退火后其分别降到 3.18 A/m 和 8.54%,表明数值模拟方法可以较好地拟合自旋阀薄膜的退火条件及实验结果,并有助于优化退火条件。

关 键 词:自旋阀薄膜;退火;数值模拟

中图分类号:TM27;TP212.12 **文献标识码**:A

Reduction of hysteresis for spin valve film by annealing method

LI Wei[1,2], LIU Hua-rui[3], REN Tian-ling[3], LIU Li-tian[3]

(1. *Key Laboratory of Optoelectronic Technology and Systems of the Ministry of Education*, *Chongqing University*, *Chongqing* 400044, *China*;
2. *Microsystem Research Center*, *Chongqing University*, *Chongqing* 400044, *China*;
3. *Institute of Microelectronics*, *Tsinghua University*, *Beijing* 100080, *China*)

Abstract: To reduce the hysteresis of spin valve films is important for fabricating Giant Magnetoresistance(GMR) sensors. This paper reports the experiment results of reducing hysteresis of the spin valve films by using an annealing method and describes numerically simulating annealing conditions and methods. By utilizing the method of numerical simulating, the annealing conditions and experiment results are simulated. The simulating results show that the numerical simulating can not only optimize annealing conditions, but also decrease a large numbers annealing experiments. Using optimized annealing conditions, the coercive force of the spin-valve film is reduced enormously but the Magnetoresistance(*MR*) of the spin-valve film can be kept a higher level. An annealing experiment and different annealing parameters show that the coercive force and *MR* of the spin-valve film respectively is 358.2 A/m and 9.24% before annealing, but they have increased to 3.18 A/m and 8.54% after annealings,

Received date: 2009-01-20; **Revised date**: 2009-04-30.

Foundation item: Supported by the National Natural Science Foundation of China(Grant No. 90407013)

which proves the numerical simulating method is conductive to the improvement of the annealing conditions.

Key words: spin-valve film; annealing; numerical simulation

1 Introduction

The spin valve has been a subject of extensive studies for more than a decade because of the giant magnetoresistance (GMR). The effect has found its application in GMR magnetic field sensors[1-6] that are widely used in both random access memory and hard drives.

The spin valve is a complex multilayer structure and its properties depend strongly on the structure of its layers and its forming process. In a general way, because of effect of the pined magnetic layer, the easy axis of free magnetic layer and the easy axis of pined magnetic layer of spin valve are parallel near, to induce hysteresis of the spin valve film. The key question is to reduce hystersis of spin valve film in fabricating linear GMR spin-valve sensor. Annealing technology as a instrument often is used to reform the structure of spin valve film[7].

In this article, we report an annealing technology to reduce the hystersis of a spin valve film and a numerical simulation method to simulate the results of annealing under different annealing parameters.

2 Experiment and results

The spin-valve film was deposited on Si/SiO_2 (100 nm) substrate by CMS-A six targets sputtering system. The spin valve has a configuration of Ta(3 nm)/NiFe(4.5 nm)/CoFe(1 nm)/Cu(1.8 nm)/CoFe(3.5 nm)/ MnIr(11 nm)/Ta (3 nm). Annealing experiment was made in homemade annealing device, magnetic field range from 0 to 0.358×10^6 A/m, temperature range from 20 ℃ to 600 ℃. To prevent film oxidation, fill N_2 in annealing device. The direction of annealing magnetic field is perpendicular to the pined direction of spin valve sample. We made a series of annealing experiments under different temperature and magnetic field values. The *MR-H* curve of samples was measured by a four-point probe system in magnetic field under room temperature. Experiment conditions and results are shown in Tab. 1.

Tab. 1 Annealing conditions and test results

Parameter	Experiment conditions		Test results	
	H ($\frac{10^3}{4\pi}$ A/m)	T (℃)	MR (%)	Hc ($\frac{10^3}{4\pi}$ A/m)
	50	100	9.12	0.94
	50	150	8.96	0.25
	50	200	8.77	0.12
	50	250	8.36	0.09
Numerical Value	100	100	9.00	0.37
	100	150	8.75	0.05
	100	200	8.66	0.036
	100	250	8.24	0.02
	150	100	6.97	0.13
	150	150	6.92	0.03
	150	200	6.85	0.024
	150	250	6.72	0.013
	200	100	4.61	0.02
	200	150	4.23	0.014
	200	200	3.75	0.01
	200	250	3.13	0.002

3 Simulation

Because the thickness of spin-valve film is about 30 nm, the spin valve film can be described by single magnetic domain model[8]. Fig. 1 is the

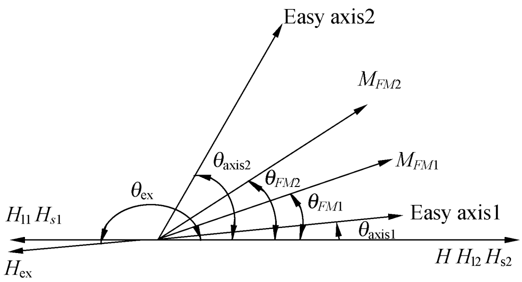


Fig. 1 Angles in single magnetic domain model

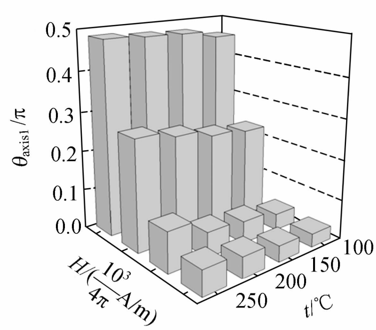
angle sketch map of single magnetic domain model. According to single magnetic domain model, the total energy of spin valve film and MR can be written:

$$E_S V=\frac{1}{2}M_{FM1}\left(H_{k1}+\frac{8M_{FM1}t_{FM1}}{w}\right)\sin^2(\theta_{FM1}-\theta_{axis1})-\frac{M_{FM1}I_1}{2w}\cos(\theta_{FM1}-\theta_{I1})+\frac{1}{2}M_{FM2}\left(H_{k2}+\frac{8M_{FM2}t_{FM2}}{w}\right)\sin^2(\theta_{FM2}-\theta_{axis2})-\frac{M_{FM2}I_2}{2w}\cos(\theta_{FM2}-\theta_{I2}),\tag{1}$$

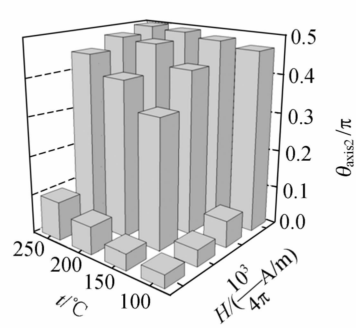
$$MR=\frac{1}{2}MR_{max}[1-\cos(\theta_{FM2}-\theta_{FM1})].\tag{2}$$

According to the energy least value condition, we can get θ_{FM2} *and* θ_{FM1} under different H. Afterward, used formula (2), we can calculate MR of sample and plot MR-H curve by Matlab software. From MR-H curve, we can obtain MR and Hc values of spin-valve film.

In our simulation, we simulated MR-H curve of spin-valve before annealing. Considering the difference of resistance of free magnetic layer with pinned magnetic layer is smaller, we can assume $I_1=I_2$. According to Fig. 1, $\theta_H=\theta_{S2}=\theta_{I2}=0$, $\theta_{S1}=\theta_{I1}=\pi$, $\theta_{ex}=\pi+\theta_{axis1}$, we can simulate the MR-H curve of spin valve film sample before annealing. In this process, we can make the figure of MR-H curve to be similar with experimental curve and to get some basic simulating parameter, such as $MR_{max}=9.24\%$, $M_{FM1}=1\,580$ emu/cm^3, $M_{FM2}=980$ emu/cm^3, $H_{ex}=1.98\times10^4$ T, $H_{k1}=1.59\times10^3$ T, $H_{k2}=1.78\times10^2$ T, $H_f=7.96\times10^2$ T, $t_{FM1}=3.5$ nm, $t_{FM2}=5.5$ nm, $w=2$ mm, $I_1=I_2=0.02$ mA. Then, using these basic parameter and changing the angle value of θ_{axis1} and θ_{axis2}, we can simulate the MR-H curve of spin valve film after annealing. When simulation MR-H curve is similar with experimental MR-H curve, we can get the angle value of θ_{axis1} and θ_{axis2} under different annealing condition. Fig. 2 shows the relation between $\theta_{axis1}/\theta_{axis2}$ and annealing condition.



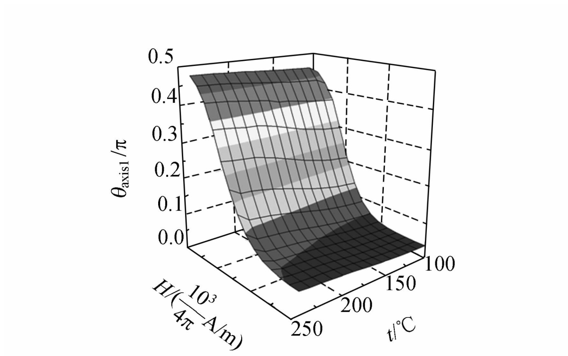
(a)



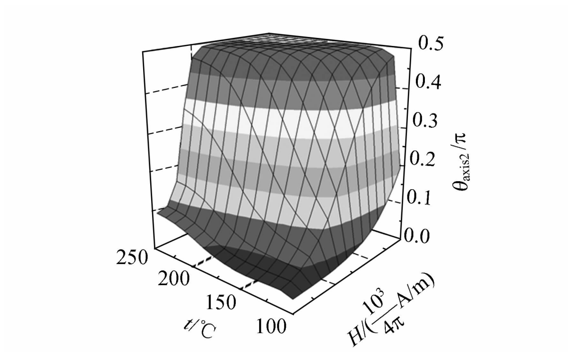
(b)

Fig. 2 Relation between $\theta_{axis1}/\theta_{axis2}$ and annealing conditions

Finally, adopting numerical value simulation method, we obtain experience formula of θ_{axis1} and θ_{axis2}, as shown in formula (3) and (4). They are function of magnetic field H and temperature



(a)



(b)

Fig. 3 Simulation between $\theta_{axis1}/\theta_{axis2}$ and annealing condition

t. Fig. 3 shows the result of simulating θ_{axis1} and θ_{axis2} under annealing condition.

$$\theta_{axis1}(H,t)=\frac{\pi}{2}\left(\frac{A_1(t)-1}{1+\exp\left(\frac{H-H_1(t)}{\Delta H_1(t)}\right)}+1\right), \quad (3)$$

$$\theta_{axis2}(H,t)=\frac{\pi}{2}\left(\frac{A_2(t)-1}{1+\exp\left(\frac{H-H_2(t)}{\Delta H_2(t)}\right)}+1\right), \quad (4)$$

where $A_1(t)$, $H_1(t)$, $\Delta H_1(t)$, $A_2(t)$, $H_2(t)$, $\Delta H_2(t)$ is function of temperature t, respectively express as follow:

$$A_1(t)=\frac{7.24}{1+\exp\left(\frac{t-161.74}{25.56}\right)}+8.47, \quad (5)$$

$$H_1(t)=116.17-14.35\exp\left[-0.5\times\left(\frac{t-250.18}{6.60}\right)^2\right], \quad (6)$$

$$\Delta H_1(t)=14.88-8.14\exp\left[-0.5\times\left(\frac{t-254.73}{9.28}\right)^2\right], \quad (7)$$

$$A_2(t)=\frac{10.55}{1+\exp\left(\frac{t-178.59}{15.46}\right)}+4.79, \quad (8)$$

$$H_2(t)=72.08-1.91\exp\left(-\frac{t-77.48}{2.83}\right), \quad (9)$$

$$\Delta H_2(t)=4.68-154.78\exp\left(-\frac{t-21.28}{39.16}\right). \quad (10)$$

4 Conclusions

According to the results of numerical value simulating, along with annealing temperature rising and annealing magnetic field enhancing, θ_{axis1} and θ_{axis2} is near $\pi/2$, but the velocity of θ_{axis2} near $\pi/2$ is faster than θ_{axis1}. Therefore optimizing annealing condition to make θ_{axis2} near $\pi/2$ for reducing hystersis of spin valve film and to keep θ_{axis1} near zero for maintaining high *MR* of spin valve film is feasible. The result of numerical value simulation afford theory gist for optimizing annealing condition. Using optimizing annealing condition ($H=2.5\pi^{-1}\times10^4$ A/m, $t=$ 150 ℃), the capability spin-valve film remarkably is improved. The coercive force and *MR* of spin-valve film respectively is 358.2 A/m and 9.24% before annealing, but the coercive force and *MR* of spin-valve film respectively is 3.18 A/m and 8.54% after annealing.

References:

[1] KOS A B, RUSSEK S E. High current density measurements of giant magnetoresistive spin-valves for magnetic recording and sensor applications[J]. *IEEE Transaction on Magnetics*, 1997, 33: 3541-3543.

[2] TONG H C, SHI X, LIU F, *et al*.. Greater than 14 Gb/in2 spin valve heads[J]. *IEEE Transaction on Magnetics*, 1999, 35: 2574-2579.

[3] PAULO P F, SUSANA C, RICARDO S, *et al*.. Spin dependent tunnel junctions for memory and read-head applications[J]. *IEEE Transaction on Magnetics*, 2000, 36: 2796-2801.

[4] DAUGHTON J M. GMR applications[J]. *Journal*

of Magnetism and Magnetic Materials, 1999,192: 334-342.

[5] QIAN ZH H,WANG D X, DAUGHTON J M,*et al.*. Linear spin-valve bridge sensing devices[J]. *IEEE Transaction on Magnetics*, 2004,40:2643-2645.

[6] PELEGRI J, EJEA J B,RAMIREZ D,*et al.*. Spin-valve current sensor for industrial applications[J]. *Sensors and Actuators A*, 2003,105:132-136.

[7] JANG S H,KIM Y W,KANG T,*et al.*. Strctural changes in the nano-oxide layer with annealing in specular spin valves[J]. *Journal of Applied Physics*, 2003,93:8388-8390.

[8] LABRUNE M, KOOLS J C S, THIAVILLE A. Magnetization rotation in spin-valve multilayers [J]. *Journal of Magnetism and Magnetic Materials*, 1997,171:1-15.

Authors' biographies:

LI Wei (1962-), male, associate professor, received his Ph. D. degree from the Department of Physics, Shandong University in 1998. He had been as a post-doctor in Institute of Microelectronics, Tsinghua University from 2004 to 2007. Now, he works at the Microsystem Research Center, Chongqing University. His Research interests are spintronics, MEMS and microsensors. **E-mail**: imeliwei@cqu.edu.cn

LIU Hua-rui(1979—), male, received his Ph. D. degree from the Institute of Microelectronics, Tsinghua University in 2006. His research interests are GMR sensor, *etc.*. **E-mail**: liu_huarui@hotmail.com.

REN Tian-ling(1971—), male, professor, received his Ph. D. degree from the Department of Modern Applied Physics, Tsinghua University in 1997. Now, he is a professor in Institute of Microelectronics, Tsinghua University. His research interests are MEMS, nano electronics and spintronics, new semiconductor memories, new materials in micro/nano Electronics, *etc.*. **E-mail**: RenTL@tsinghua.edu.cn

LIU Li-tian(1947—), male, professor, graduated from the Department Electronic Engineering, Tsinghua University in 1970. He is a professor of the Device Research Division in Institute of Microelectronics, Tsinghua University. His research interests are MEMS, smart sensors, bio-chip and novel semiconductor devices. **E-mail**: liulitian@mail.tsinghua.edu.cn