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# On the Ferromagnetic Interlayer Coupling in Exchange-Biased Spin-Valve Multilayers

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**Abstract**—The ferromagnetic interlayer coupling in sputter-deposited permalloy/copper/permalloy exchange-biased spin valve multilayers has been measured as a function of the copper thickness. The variation with thickness may, for  $t_{Cu} > 1.7$  nm, be analyzed in terms of the Neel model for magnetostatic coupling due to correlated interface roughness, using parameters which are consistent with the observed microstructure.

## I. INTRODUCTION

Exchange-biased spin valve multilayers [1] are viable candidates for application in thin film magnetic recording heads for hard disk [2] or tape applications [3], due to their sensitivity to small magnetic fields, in particular when permalloy ( $Ni_{80}Fe_{20}$ ) is used as the sensitive ferromagnetic layer. In order to achieve this sensitivity, one would prefer a situation which is such that the free and biased (pinned) layers are not, or only weakly, magnetically coupled.

It has been reported [4,5,6,7] that some coupling does exist in practical samples. For spin-valve multilayers using permalloy or a Ni-rich ternary Ni-Co-Fe alloy as the ferromagnetic material, one finds predominantly ferromagnetic coupling [4,6,7], while for spin-valves using Co as the ferromagnetic material, an oscillatory behaviour is observed [5]. The latter behaviour has been attributed to oscillating exchange coupling through an RKKY-like mechanism. For the mechanism in the case of ferromagnetic coupling in permalloy-based spin-valve structures, a "pinhole" mechanism has been put forward [6]. In this paper, we will further discuss the origin of the ferromagnetic coupling in permalloy-based spin-valves, whereby the role of magnetostatic interactions due to non-flatness of the layers is taken into account.

## II. EXPERIMENTAL RESULTS AND DISCUSSION

Series of multilayers with general structure Si(100)/3nm Ta/8 nm  $Ni_{80}Fe_{20}$ /  $t_{Cu}$  Cu/ 6 nm  $Ni_{80}Fe_{20}$ / 8 nm FeMn/ 3.5 nm Ta have been grown with  $t_{Cu}$  varying between 1.0 and 4.0 nm by DC-magnetron sputtering. The films discussed here have

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been prepared at a pressure of 5 mTorr Ar. X-ray diffraction showed the films to be polycrystalline with a strong (111) texture. Plan view Transmission Electron Microscopy (TEM) analysis was performed on films with the structure substrate/3nm Ta/12.5 nm  $Ni_{80}Fe_{20}$ / 3.0 nm Ta, where the substrates are microfabricated  $Si_3N_4$  membranes in order to determine the grain sizes. This sample composition was chosen, in order to enable one to study the size of the grains, at the level of the  $Ni_{80}Fe_{20}/Cu/Ni_{80}Fe_{20}$  interfaces. The results of this analysis are shown in fig. 1. It can be seen that the films are polycrystalline with typical grain sizes of 10 nm. Atomic Force Microscopy (AFM) showed the mean value of the protrusions of the surface of a complete multilayer to be around 0.4 nm.

The interlayer coupling energy was determined by analyzing [6] the shape of measured magnetoresistance curves. For coupling energies  $J$  which are much smaller than the biasing energy ( $J$  typically below  $0.05$  mJ/m<sup>2</sup>), the biased layer is unaffected, and the Zeeman energy associated with the offset field of the transition of the free layer ( $H_0$ ) gives the coupling strength. For larger coupling strength, a more thorough analysis is required, explained in ref. [6]. The results are shown in fig. 2. It can be seen that the interlayer coupling is always positive and essentially monotonously decreasing as the copper thickness increases. A small plateau (or shallow minimum) may be discerned around 2.0 nm. Two regimes may be distinguished: for thin copper interlayer thicknesses (up to 1.7 nm), one observes a very rapid decrease of the coupling strength

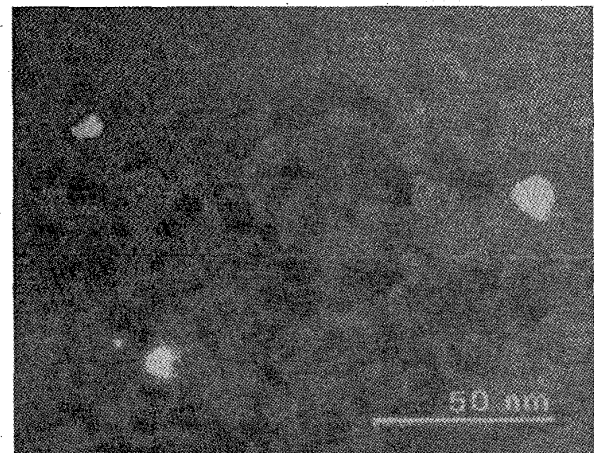


Fig.1: Plan view TEM micrograph showing grain size

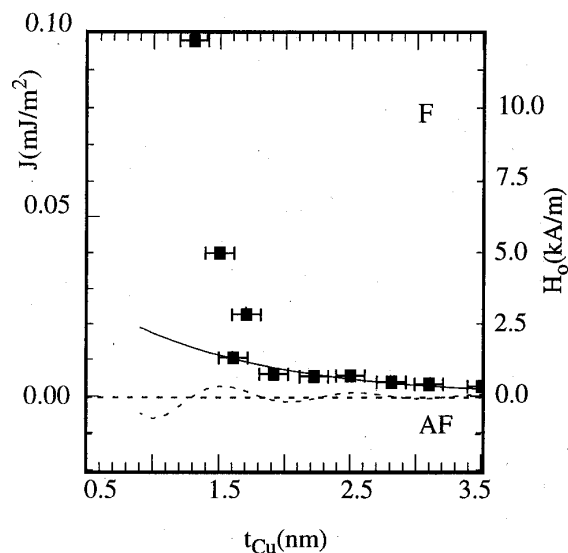


Fig.2: Measured interlayer coupling energy as a function of copper thickness (squares). Solid Line = fit with the Neel model (eq.1) ; Dashed line: Oscillating exchange coupling (eq.2) for fit parameters as given in the text.

with increasing thickness. For thicker Cu spacers, the coupling strength decreases at a much lower pace.

Bearing in mind that the observed coupling strength must be considered as the cumulative effect of a number of mechanisms, dominated by the strongest one, the role of different coupling mechanisms is discussed now. The measured data for  $t_{Cu} > 1.7$  nm are compared to two models for the coupling mechanisms (Neel coupling and oscillating exchange coupling) in order to assess the importance of each mechanism

The Neel model describes the magnetostatic coupling caused by the correlated waviness of the magnetic layers in non-ideal films ("orange-peel coupling") [8]. In this model, the coupling energy  $J$  of two ferromagnetic films (saturation magnetization  $M, M'$ ) separated by a spacer with thickness  $t_{Cu}$  which have a two-dimensional sinusoidal waviness with amplitude  $h$  and wavelength  $\lambda$  is given as:

$$J = \frac{\pi^2}{\sqrt{2}} \cdot \frac{h^2}{\lambda} \cdot \left( \mu_o M M' \right) e^{-\frac{2\pi\sqrt{2}t_{Cu}}{\lambda}} \quad (1)$$

We have analyzed our data in terms of this model, using  $h=0.4$  nm,  $\lambda=10$  nm and  $M=M'=1T$ . The resulting coupling strength  $J(t_{Cu})$  is plotted in fig. 2 as a solid line. It can be seen that this -relatively simple- model gives a very reasonable description of the data, using these parameters which are consistent with the observed microstructure.

In addition to this magnetostatic coupling, one would expect [9] an oscillatory exchange coupling given by:

$$J = \frac{J_o}{t_{Cu}^2} \sin\left(\frac{2\pi t_{Cu}}{\Lambda} + \phi\right) \quad (2)$$

where  $\Lambda$ , and  $\phi$  are the wavelength and phase of the coupling. This form is plotted in fig. 2 as the dashed line. We have used :  $J_o = 0.01$  mJ/m<sup>2</sup>,  $\phi = 1.4\pi$  and  $\Lambda = 1$  nm, consistent with observations on permalloy/Cu multilayers[10].

In the regime where  $t_{Cu} < 1.7$  nm, the measured coupling strength is considerably larger than the values predicted by both models. It is proposed that this regime is dominated by bridging sites causing direct contact between ferromagnetic layers ("pinholes"). This contribution rapidly decreases as the interlayer becomes thicker than a few times the size of typical protrusions (0.4 nm).

The regime with  $t_{Cu} > 1.7$  nm is described more satisfactorily by the two mechanism considered. It can be seen that the Neel model accounts for the largest contribution, while the contribution of the oscillating exchange coupling remains relatively modest, although noticeable.

It was found earlier [11] that an increase of the pressure during sputter deposition resulted in an increase of the surface roughness, and subsequently to an increase in the ferromagnetic coupling strength. This observation is consistent with the interpretation of the F coupling in terms of the Neel model.

### III IMPLICATIONS FOR SENSOR APPLICATIONS

The magnetization switching mechanism of the free layer is essentially determined by the ratio of the coupling strength over the anisotropy field[12]. For coupling strengths which are larger than the anisotropy field, the sensitive part of the  $R(H)$  curve is found at an offset field.

In the lower copper thickness regime, the coupling strength is much larger than the anisotropy field, and highly sensitive to thickness variations. This implies that this thickness range is less desirable from a practical point of view, although the highest values of the magnetoresistance  $\Delta R/R$  are found in this range [4]. When manufacturing a sensor device comprising a multilayer in the higher thickness range, it is important to control the substrate morphology, since the amplitude of the interface waviness ( $h$  parameter in eq. 1) influences the strength of the coupling field considerably.

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