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# Magnetic properties and interlayer coupling of sputtered Ni/V multilayers

K. Benkirane[a,*], R. Elkabil[a], M. Lassri[b], M. Abid[b], H. Lassri[b], A. Hamdoun[a], R. Krishnan[c]

[a] Laboratoire de Traitement D'information, Faculté des Sciences, Ben'Msik Sidi-Othmane, B.P. 7955-Sidi-Othmane, Casablanca, Morocco
[b] Laboratoire de Physique des Matériaux et de Micro-électronique, Faculté des Sciences Ain Chock, Université Hassan II, B.P. 5366 Mâarif, Route d'El Jadida, km-8, Casablanca, Morocco
[c] Laboratoire de Magnétisme et d'Optique, URA 1531, 45 Avenue des Etats Unis, 78035 Versailles Cedex, France

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**Abstract**

The magnetic properties of sputtered Ni/V multilayers have been studied in a vibrating sample magnetometer, torque magnetometer and by ferromagnetic resonance (FMR). The magnetization decreases with decreasing Ni layer thickness, which is an indication of the structural imperfections at interface. The interface contribution to the magnetic anisotropy is practically negligible. The spin-waves resonance modes were observed for perpendicular geometry, which implied that spin waves were sustained by the whole film and propagated through V layers in some Ni/V multilayers. The relation of the resonance field $H_n$ with the mode number n obeys the so-called $n^2$ law and the interlayer exchange constants were determined.


*Keywords:* Ni/V multilayers; Magnetization; Magnetic anisotropy; Ferromagnetic resonance; Spin-waves

## 1. Introduction

The magnetic properties of artificial magnetic multilayers and ultrathin ferromagnetic films have been extensively studied in recent years. Very large perpendicular magnetic anisotropy exists in some of these thin-film systems and is particularly interesting from a fundamental point of view as well as for their potential application to recording media [1,2]. The magnetic anisotropy may be caused by various mechanisms, including shape anisotropy, magnetocrystalline anisotropy, magnetostriction, or the reduced symmetry at interfaces.

Research on interlayer exchange coupling of magnetic multilayers and double layers is becoming active, and many characteristics of interlayer coupling have been discovered, such as antiferromagnetic, ferromagnetic, and oscillating exchange couplings [3,4].

The magnetic properties of multilayers are strongly dependent on their detailed structure and composition, which are determined by the growth conditions used during fabrication [5–7]. For example, the degree of mixing between adjacent layers determines the amount of Ni able to contribute to the magnetic properties of the film, and the degree of crystallographic texture within the layers, combined with any surface anisotropy present determines the overall anisotropy of the multilayers.

In this paper we present magnetization and FMR measurements performed on Ni/V multilayers prepared by RF sputtering.

## 2. Experimental

The multilayers were deposited onto water-cooled glass substrates by RF diode sputtering. The chamber was first evacuated to a pressure of 1–2 × $10^{-7}$ Torr using a turbomolecular pump. Argon of 5 N purity was used as the sputter

* Corresponding author.
*E-mail address:* karbenkirane@yahoo.fr (K. Benkirane).

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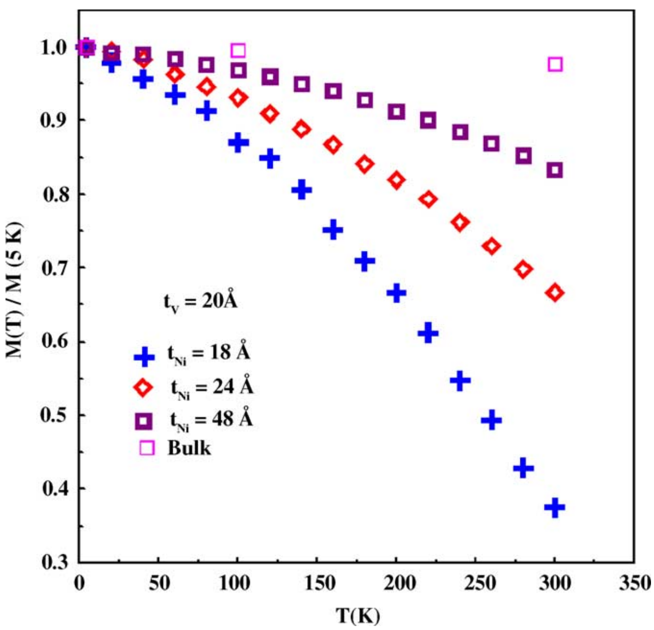


Fig. 1. Magnetization of several (111) Ni/V multilayers versus temperature.

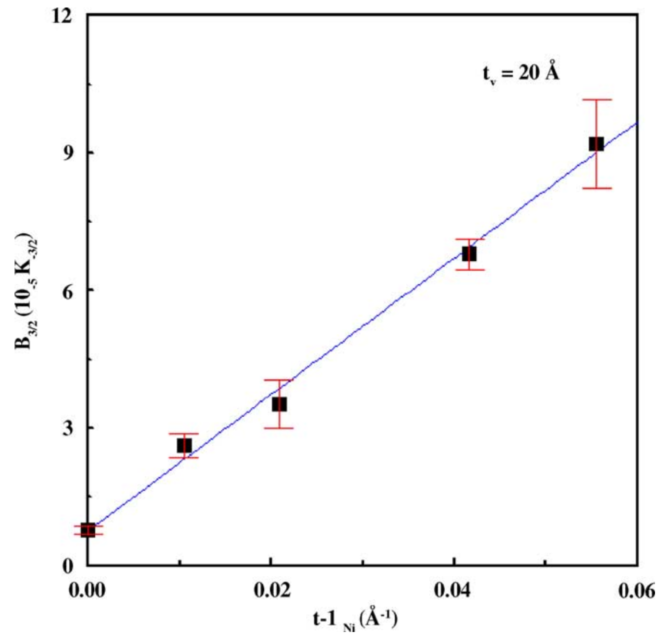


Fig. 2. The $t_{Ni}^{-1}$ dependence of the B.

gas and its pressure was kept constant at $6 \times 10^{-3}$ Torr. The Ni layer thickness $t_{Ni}$ varied from 18 to 96 Å and that of V layer $t_V$ was fixed at 20 Å. The number $N$ of bilayers were in the range of 5–15. All the samples were grown on vanadium buffer layers100 Å thick. In all the cases the first and the last layers were V. In what follows, the growth parameters of the samples will be indicated as $(t_{Ni}/t_V)_N$. Magnetization $4\pi$M was measured using a vibrating sample magnetometer in applied magnetic fields up to 2 T at room temperature. Ferromagnetic resonance studies were carried out at 9.8 GHz with the static field applied both perpendicular ($H_\perp$) and parallel ($H_{||}$) to the film plane. A torque magnetometer was used to measure the anisotropy at 5 K in applied magnetic fields up to 1.5 T.

## 3. Results and discussion

The low-temperature magnetization was studied in detail for a few samples. Plots of the magnetization, for different thicknesses of Ni layers, versus temperature were made for the Ni/V multilayers (Fig. 1). It can be noticed that the magnetization decreases with a decrease in Ni layer thickness. Our results would indicate that the interface is diffuse due to the structural imperfection effects (contamination, diffusion, island growth).

According to spin-wave theory, the temperature dependence should follow the relation:

$$\frac{[M(5K) - M(T)]}{M(5K)} = BT^{3/2}. \tag{1}$$

In all cases this behaviour is observed for temperatures as high as $T_C/3$ (where $T_C$ is the Curie temperature). The spin-wave constant $B$ decreases from $92 \times 10^{-6}\,K^{-3/2}$ for $t_{Ni}$ = 18 Å to $26 \times 10^{-6}\,K^{-3/2}$ for $t_{Ni}$ = 96 Å. These values are much larger than the value of $7.5 \times 10^{-6}\,K^{-3/2}$ found for bulk Ni.

The $B$ versus $1/t_{Ni}$ is plotted for the samples with $18 \leq t_{Ni} \leq 96$ Å in Fig. 2. It is seen that the experimental points align well in a straight line. The values extrapolated to $1/t_{Ni}$ = 0 are in good agreement with those found for the bulk Ni. It was observed that the parameters $B$ in Eq. (1) depend on $t_{Ni}$ according to:

$$B(t_{Ni}) = B_\infty + \frac{B_S}{t_{Ni}} \tag{2}$$

where $B_\infty$ is the bulk spin-wave parameter of Ni and $B_S$ surface $B$ value. The interface anisotropy strongly affects the thickness dependence of the magnetization. The linear relation between the spin-wave parameter $B$ and the reciprocal of the magnetic film thickness was reported also by Gradmann and co-workers [8,9] for Fe(1 1 0) films on W(1 1 0).

Torque studies yield the effective anisotropy $K_{eff}$. The $t_{Ni}$ dependence of $K_{eff}$ could be analyzed on the basis of the well known phenomenological model which predicts the following relation:

$$K_{eff} = K_V + \frac{2K_S}{t_{Ni}} \tag{3}$$

where the volume anisotropy $K_V = K_{crys} - 2\pi M^2$ ($K_{cryst}$ being the crystalline anisotropy) and $K_S$ is the surface anisotropy arising from the surface Ni atoms. Fig. 3 shows the results at 5 K in order to avoid the effects arising from the lowering of $T_C$ for thinner Ni layer samples. The present results shows that there is no contribution to $K_S$ from the Ni atoms. This is in agreement with our result on Ni/Ag [10] and

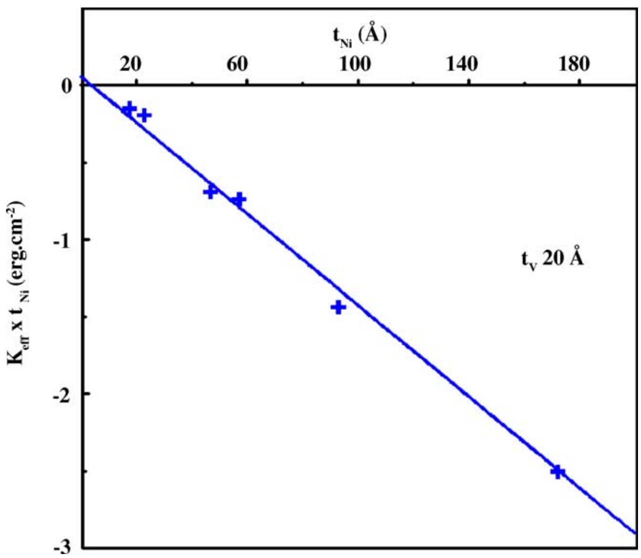


Fig. 3. Variation of the product $K_{eff} \times t_{Ni}$ with $t_{Ni}$ at 5 K.

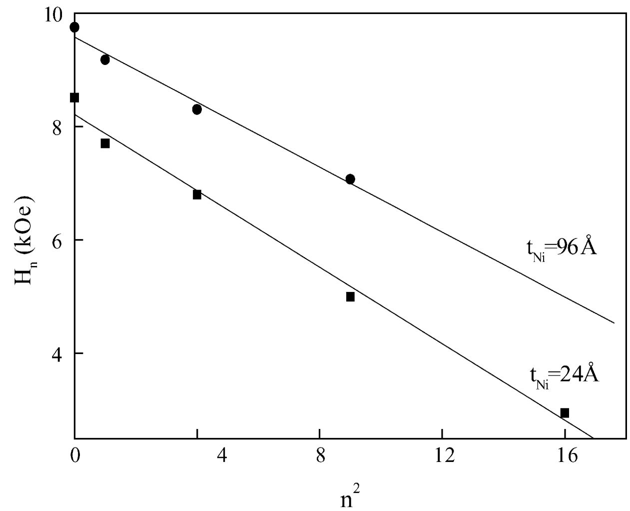


Fig. 5. Resonance field $H_n$ in perpendicular orientation versus $n^2$.

on Ni/Pd by den Broeder et al. [11]. However, we have shown that in the Ni/Pt system a strong perpendicular anisotropy is present arising from the surface anisotropy [12]. It is well known that the surface anisotropy arises from the local crystal fields and hence should not only depend on the state of the interface but also on the electronic structure of the neighboring metal. From the slope of the straight line in Fig. 3, the volume anisotropy is found to be $-1.5 \times 10^6$ erg/cm$^3$.

In FMR, when the magnetic field was parallel to the film plane, only one resonance peak related to the uniform mode appeared. When the field was applied perpendicular to the film plane, multiple resonance peak spectra were observed for some samples. A typical perpendicular FMR spectrum of the sample with $t_{Ni}$ = 96 Å was shown in Fig. 4. The resonance field $H_n$ obeyed the so-called $n^2$ law, as shown in Fig. 5. The excitation of spin waves implies that the multilayers are coupled by the interlayer exchange interaction into a single magnetic system, and the standing spin waves with different wavelengths are sustained by the whole film thickness instead of by individual Ni layers. Thus the spin waves can propagate through V layers. The appearance of spin wave modes with odd and even n may be understood as being due to inhomogeneities in the multilayers.

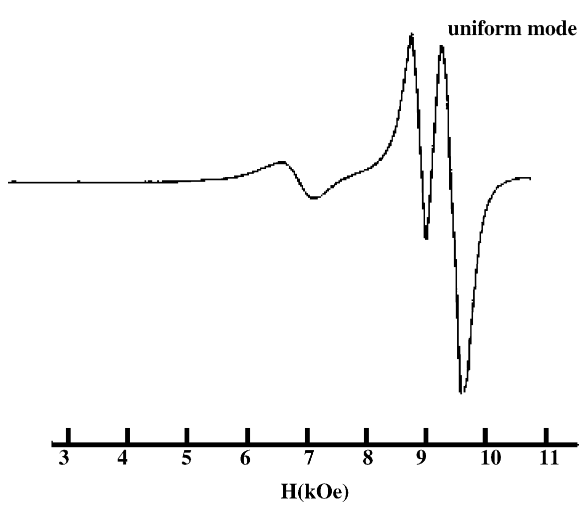


Fig. 4. FMR spectra for $(Ni_{96\,Å}/V_{20\,Å})_5$ multilayer with applied dc field perpendicular to the film plane at 300 K.

A model for spin waves in ferromagnetic/weak ferromagnetic multilayer proposed by van Staple et al. [13] was extended to the case of ferromagnetic/nonmagnetic multilayers by Wang et al. [14]. In perpendicular geometry, for a single magnetic layer in multilayers, the spin wave dispersion relation can be expressed by

$$\frac{\omega}{\gamma} = H_n - 4\pi M_{eff} - \frac{2Ak^2}{M}, \quad (4)$$

where $H_n$ is the resonance magnetic field, $4\pi M_{eff}$ is the effective magnetization, $A$ is the exchange coupling constant in the magnetic layer and $k$ is the spin wave number. When the magnetic layers couple to each other by interlayer exchange interactions, a collective spin wave mode may appear with overall wave vector $K$. $K$ and $k$ are related by the dispersion relation [13]

$$\cos(k\,t_{Ni}) = \cos(K\,t_{Ni}) + \left(\frac{A}{t_{Ni}\,A_g}\right) k\,t_{Ni} \sin(k\,t_{Ni}), \quad (5)$$

where $t_{Ni}$ is the thickness of a single magnetic layer and $A_g$ is the interlayer exchange coupling constant (per area). In the approximation for small $kt_{Ni}$ and $Kt_{Ni}$,

$$K = k\left(1 + \frac{2A}{t_{Ni}Ag}\right)^{1/2}. \quad (6)$$

Then the spin wave dispersion relation of the multilayer film can be expressedby

$$\frac{\omega}{\gamma} = H_n - 4\pi M_{eff} - \left(\frac{2Ak^2}{M}\right)\left[\frac{1}{(1 + 2A/t_{Ni}Ag)}\right]K^2. \quad (7)$$

$K$ depends on the boundary conditions. For an ideal free boundary, $NKt_{Ni} = n\pi$, $n$ is an integer. Thus the spin wave spectra should satisfy a $n^2$ law.

Then we can estimate the interlayer coupling constant $A_g$ by analyzing the experimental results shown in Fig. 5 with Eq. (7). In order to determine the interlayer exchange coupling constant A, we performed spin-wave resonance experiment on a single-layer Ni thin film made under the same conditions as that of the Ni layers in multilayers. From this experiment, $A = 10^{-6}$ erg/cm was obtained. We assume that the Ni layers in multilayers have the same exchange coupling constant as a Ni single-layer film. Using this value, the interlayer coupling constant was derived as $A_g = 0.3$ erg/cm$^2$. A positive sign of $A_g$ means ferromagnetic coupling and agrees with our expectation.

## 4. Conclusions

In conclusion, we have studied Ni/V multilayers prepared by RF sputtering. The saturation magnetization of Ni/V multilayer films is found to decrease with decreasing Ni layer thickness. These results can be explained in terms of the structural imperfections near the Ni–V interface. The spin-wave constant B is found to decrease inversely with $t_{Ni}$. The surface and volume contributions to the anisotropy have been determined at 5 K. The spin-wave modes were analyzed with the existing spin wave resonance theory of multilayers and the interlayer exchange coupling constant was calculated.

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