INTERFACIAL MAGNETISM AND ANISOTROPY IN Fe/Pt MULTILAYERS

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Abstract. *Magnetic properties of rf-sputtered Fe/Pt multilayers with fixed Pt-layer thickness ($t_{Pt} = 15\overset{o}{A}$) and variable Fe-layer thickness ($2.4\overset{o}{A} \leq t_{Fe} \leq 53\overset{o}{A}$) have been studied by magnetisation using a vibrating sample magnetometer at room temperature. The results show that in the Fe/Pt interfaces, which formed by a $Pt-Fe$ alloy, a positive polarisation of the induced Pt-moment with respect to Fe-moment was found and a perpendicular interfacial anisotropy was evidenced. These behaviors are described in terms of the hybridisation between the $3d(Fe)$ and $5d(Pt)$ states.*

I. INTRODUCTION

T/X multilayers consist of the magnetic transition metals $T(T = Fe, Co$ and $Ni)$ and other non-magnetic transition metals X, which are heavy transition metals ($HT = Cu, Ag, Pd, Pt, ...$) or light transition metals ($LT = Sc, Ti, V, Y$, rare earth elements, ...) exhibit several novel physical properties, such as giant magnetoresistance, oscillating interlayer coupling, perpendicular magnetic anisotropy [1]. These multilayers, therefore, attached considerable attention. For the understanding of such effects, it is important to learn what is magnetic behavior at the interfaces, where questions concerning the magnetic moments, the type of magnetic exchange coupling and spin orientation may be answered. In this context, the hybridisation between the $d(T)$ and $d(X)$ states, which occur in the interfaces was thought to be the reason [2,3]. In more details, it has been predicted that the $d(T)$-$d(HT)$ hybridisation drives an out-of- plane spin orientation for the Fe/HT multilayers (denoted as group I multilayers) and the $d(T)$-$d(LT)$ hybridisation drives an in-plane spin orientation for the Fe/LT ones (group II multilayers). Additionally, hybridisation effects also govern the magnetic moments induced on the HT and LT sites. It is expected that a positive HT magnetic moment is present in Fe/HT multilayers and a negative LT one in those of Fe/LT [4].

Fe/Pt multilayers are one of the well-known examples. As Pt is a heavy transition element, the multilayers under consideration belong to group I. In fact, an interfacial positive anisotropy, which is in good agreement with above mentioned proposal, was evidenced

[5]. Magnetic properties of these Fe/Pt multilayers with variable ratios of Fe-thickness (t_{Fe}) and Pt-thickness (t_{Pt}) have also been studied by means of Mössbauer spectroscopy [6] and Kerr effect [7].

In this paper, analysis of magnetisation data measured at helium liquid and room temperatures are presented. The role of the $3d(Fe)-5d(Pt)$ hybridisation on the enhancement of the magnetisation and on the perpendicular interfacial anisotropy is discussed.

II. EXPERIMENTS

Fe/Pt multilayers were deposited onto glass substrates at room temperature by cathode rf-sputtering. The thickness of the Pt layers was kept constant ($t_{Pt} = 15\,\mathring{A}$) while the thickness of the iron layer (t_{Fe}) was varied in the range of $2.4 \div 53\ \mathring{A}$. The number of periods n was varied from 5 to 22. The thickness of the elemental layers was controlled during deposition by the reflectivity of low-angle X-ray. These artificial multilayers were covered with a 10 nm-thick Pt top-layer to prevent corrosion and oxidation.

For the samples under consideration, the global structure and the room-temperature conversion electron M"ossbauer spectrometry were investigated [8]. The results show that the thickness of the iron layer must be enough for the centre of the iron layer to be constituted of pure iron. Combining these data, it was estimated that the space of the interface region t_{tr} is about $20\ \mathring{A}$.

Magnetisation and magnetic hysteresis loops were measured at 300 K with a vibrating sample magnetometer (VSM) in the applied magnetic fields up to 1.3 T along the film-plane and film-normal directions.

III. RESULTS AND DISCUSSION

Fig. 1 presents the magnetic hysteresis loops measured at room temperature for several Fe/Pt multilayers with the magnetic field applied in the film-plane and along the film-normal direction. For all samples, the coercive field ($\mu_0 H_C$) ranges from 2.8 mT to 4.8 mT. The values of the saturation magnetisation (M_S) calculated per volume unit is listed in table 1. The magnetisation (M_0) with respect to the magnetic volume, $M_0 = M_S(\Lambda/t_{Fe})$, is also listed in table 1 and plotted as a function of the Fe-thickness in fig. 2. For comparison, the data published by Katayama et al [5] and Fnidiki et al. [8] are also included. One finds that, at $T = 300K$, M_0 initially increases strongly with increasing t_{Fe}, then tends to saturate with a magnetisation value of 2.5 T, which excesses that (2.2 T) of the bulk Fe, in the high t_{Fe} region. This observation is in good consistence to that already reported in [5]. The small magnetisation value with respect to the bulk Fe-magnetisation is due to the low Curie temperature of the Fe-Pt alloy in the samples with low Fe-layer thickness. At low temperatures (i.e. at $T = 5K$), M_0 of the Fe/Pt multilayers, however, is always larger than that of bulk Fe for all ranges of Fe-layer thickness.

Table 1: Magnetic data for the Fe/Pt multilayers: saturation magnetisation per volume unit (M_S), magnetisation with respect to Fe volume (M_0), anisotropy ($\mu_0 H_A$) and coercive ($\mu_0 H_C$) fields.

t_{Pt}(Å)	t_{Fe}(Å)	n	M_s(T)	M_0(T)	($\mu_0 H_A$)(T)	($\mu_0 H_C$)(mT)
15	2.4	22	0.148	1.07	0.05	3.0
15	8.4	12	0.716	1.99	0.81	4.6
15	9.0	15	0.772	2.06	1.06	4.6
15	12	15	1.013	2.28	1.31	4.8
15	21	15	1.395	2.44	2.00	4.8
15	34	10	1.729	2.49	2.68	4.6
15	53	5	1.962	2.44	2.80	2.8

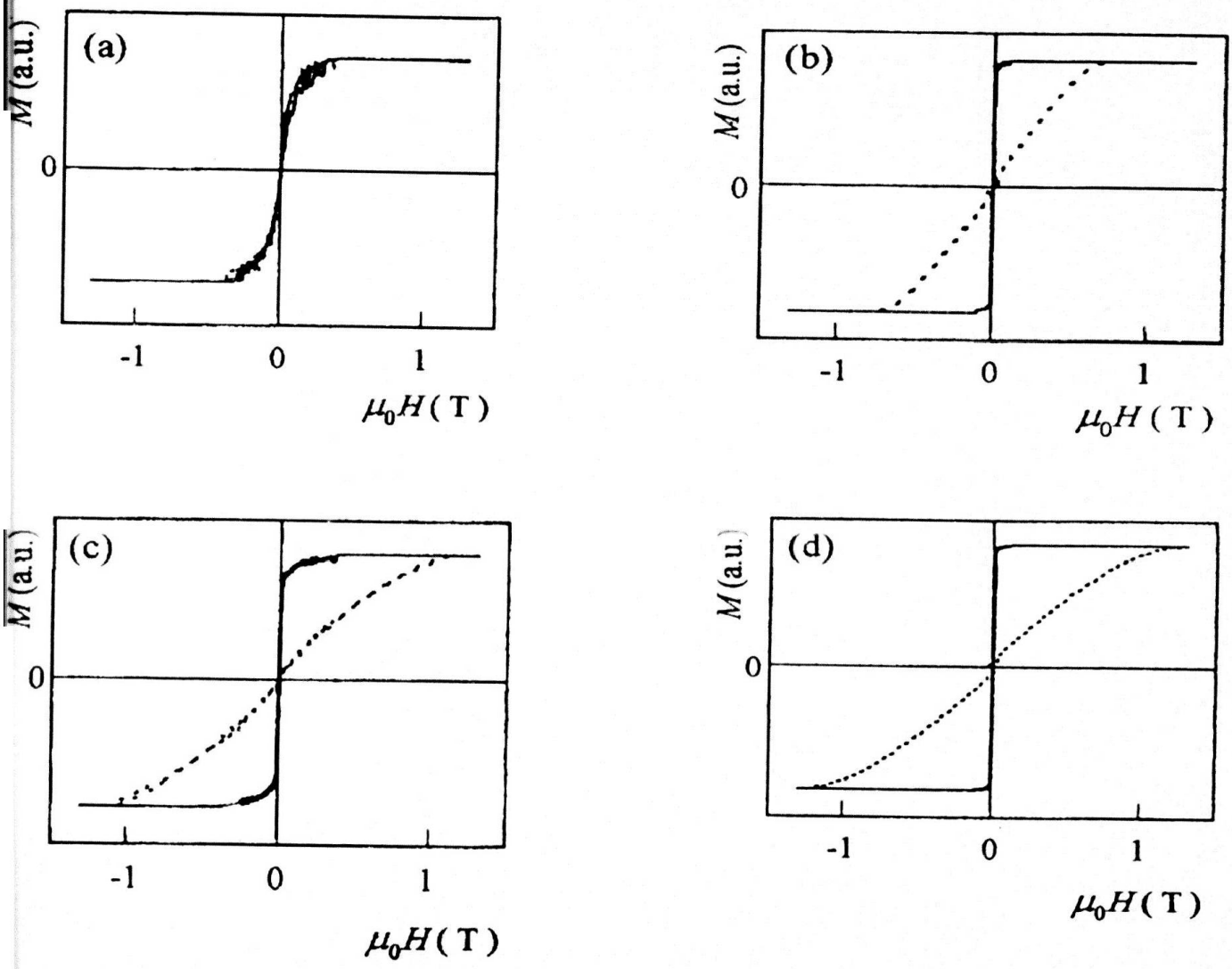

Fig. 1: Magnetic hysteresis loops with the magnetic field applied in the film-plane (solid curve) and along the film-normal (dash curve) directions for the Fe/Pt multilayers. $(a) - t_{Fe} = 2.3\,\mathring{A}$; $(b) - t_{Fe} = 8.4\,\mathring{A}$; $(c) - t_{Fe} = 9\,\mathring{A}$; and $(d) - t_{Fe} = 12\,\mathring{A}$. For the value of saturation magnetisation, see table 1.

Data presented in fig. 2 are values averaged over the whole Fe thickness. In agreement with the results of the structural and Mössbauer studies mentioned above, one can describe the multilayers by considering that (i) the inner Pt subsystem is non magnetic, (ii) the Pt-Fe interface of thickness $2t_{tr}$ and (iii) the α-Fe magnetic subsystem of thickness $t_m(= t_{Fe} - t_{tr})$. In this context, the measured magnetisation of the samples is related to the magnetisation M_{Fe} of the $\alpha - Fe$ in the core, the magnetisation $M_{Fe,tr}$ and $M_{Pt,tr}$ in the interfaces as the following:

$$M_0 t_{Fe} = 2(M_{Fe,tr} + M_{Pt,tr})t_{tr} + M_{Fe}(t_{Fe} - t_{tr}). \tag{1}$$

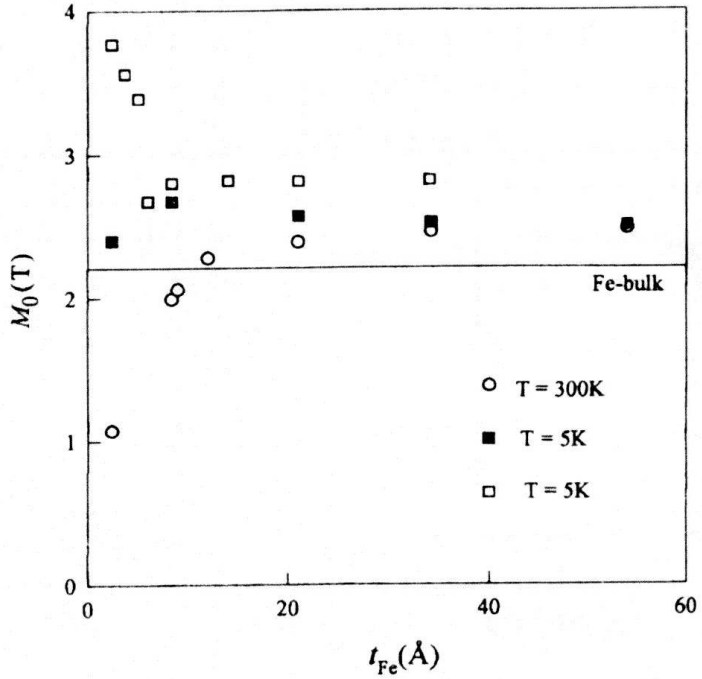

Fig. 2: Variation of M_0 as a function of the t_{Fe} for the Fe/Pt multilayers. (○) $- T = 300K$, (■) $- T = 5K$[8] and (□) $- T = 5K$[5].

Assuming that the composition $Fe : Pt$ at the interfaces is 50:50 and the magnetic moment of Fe in the interfaces ($M_{Fe,tr}$) is the same as that in the Fe core (M_{Fe}), equation (1) can be written as

$$M_0 t_{Fe} = M_{Pt} t_{tr} + M_{Fe} t_{Fe}. \tag{2}$$

For the samples under consideration (i.e., $t_{Pt} = 15\mathring{A}$ and $t_{Fe} = 2.4 \div 53\mathring{A}$), a plot of $M_0 t_{Fe}$ vs. t_{Fe} is presented in fig. 3, from which we obtain $M_{Fe} = 2.21\ T(2.18\ T)$ and $M_{Pt} t_{tr} = 0\ T.m(2.55 \times 10^{-10} T.m)$ at $300K(5K)$. Taking the value of t_{tr} as mentioned above, we derived $M_{Pt} = 0.125T$ at $5K$.A value about $0.43\mu_B/Pt\text{-}at$, thus, was estimated for the induced $5d(Pt)$-magnetic moment in the Fe/Pt interfaces. A similar value (of $0.37\mu_B/at$) has been reported for Pd in the Co/Pd interfaces [9]. The $3d(Fe)$-$5d(Pt)$ hybridisation was proposed to result in a positive 5d-polarization (with respect to the 3d moment) and then to the enhancement of the magnetisation in the $Pt-Fe$ alloys [4,10]. In their work, Mirbt et al. [4] have theoretically pointed out that a ferromagnetic coupling between the $d(HT)$ and $3d(T)$ moments is favoured when a magnetic $T(= Fe, Co, Ni)$

surface (or, in general, interface) is covered by a few layers of a non-magnetic HT element such as Cu, Ag, Pd, Pt.... At present, the mechanism of the $3d(Fe)$-$5d(Pt)$ ferromagnetic spin ordering can be understood by a simple model with rectangular local density of states of the $3d$ and $5d$ electrons as the following.

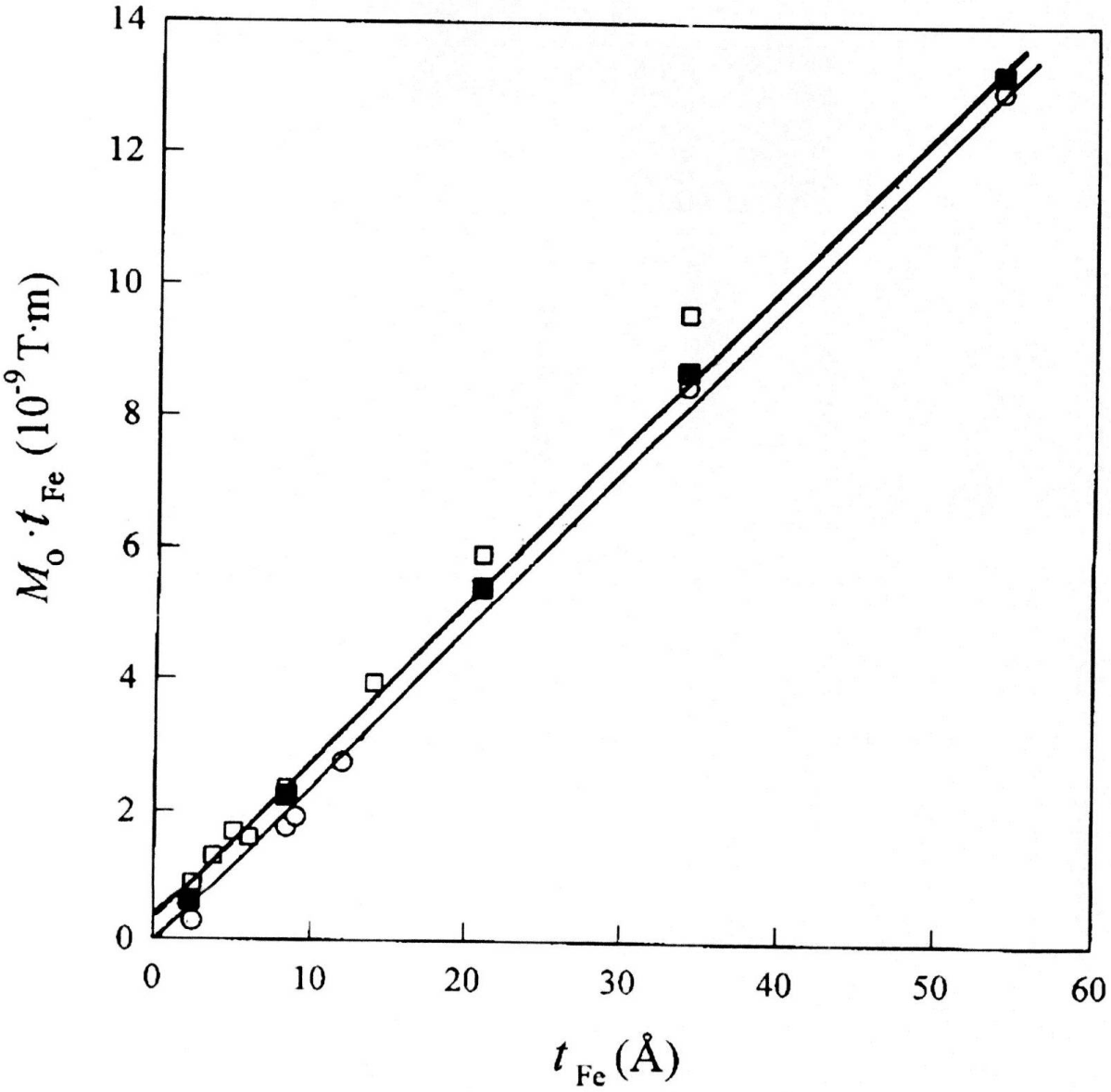

Fig. 3: Variation of $M_0 t_{Fe}$ as a function of the t_{Fe} for the Fe/Pt multilayers. (○) – $T = 300K$, (■) – $T = 5K$[8] and (□) – $T = 5K$[5].

In fig. 4, the rectangles denote the schematic local density of states of the $3d$ states of Fe and $5d$ states of Pt. The $5d(Pt)$ states are positioned at energies lower than those of the $3d(Fe)$. Due to the $3d$-$3d$ splitting, the spin-up $3d(Fe)$ subband shifts to lower energies and therefore is closer to the $5d(Pt)$ states. The $3d(Fe)$-$5d(Pt)$ hybridisation of the spin-up states is stronger than that of the spin-down states. The larger energy-separation for the down-spin electrons leads to less hybridisation than for the up-spin electrons. A direct consequence is that more spin-up $5d(Pt)$-electrons appear in the lattice and a positive moment is induced on the Pt sites.

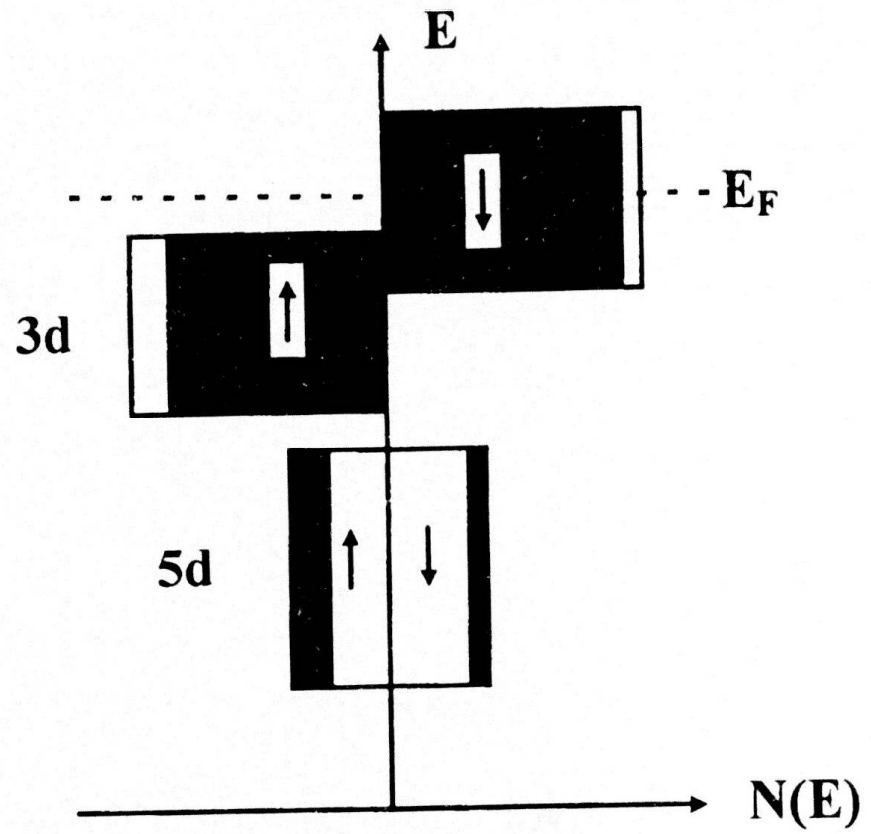

Fig. 4: Schematic illustration for the $3d(Fe)$-$5d(Fe)$ ferromagnetic spin ordering in the Fe/Pt multilayers.

The magnetic anisotropy is inferred from fig. 2. For almost all samples investigated, the in-plane direction is always easy to magnetise. The sample with $t_{Fe} = 2.4\,\mathring{A}$, however, shows an approximate isotropy. It could be due to a perpendicular anisotropy, which roughly cancels the shape anisotropy. This finding is in good agreement to that reported in [5].

The intrinsic anisotropy constant K_{intr} has been evaluated by $K_{intr} = K_A - (M_S^2)(t_{Fe}/\Lambda)/2\mu_0$, where the anisotropy energy $K_A = (\mu_0 H_A M_S)/2$. The phenomenological relationship between the interface (K_S), volume (K_V) and the intrinsic (K_{intr}) anisotropies is usually given as

$$t_{Fe}K_{intr} = 2K_S + t_{Fe}K_V. \tag{3}$$

From the plot of $t_{Fe} \times K_{intr}$ *versus* t_{Fe} (fig. 5), we deduced that the interfacial perpendicular magnetic anisotropy constant $K_S = 0.3mJ/m^2$ and the volume contribution $K_V = -0.5MJ/m^3$. These obtained results are comparable to those already reported for the Fe/Pt systems [5], but larger than those deduced for the Fe/Ti and Fe/V multilayers, where the interfaces are paramagnetic at room temperature and the perpendicular anisotropy is caused by the Fe-topmost layers [11,12]. At present, the stronger perpendicular anisotropy may be caused by an interfacial anisotropy of the same sign as that originates from by the surface (and/or the topmost Fe-layers).

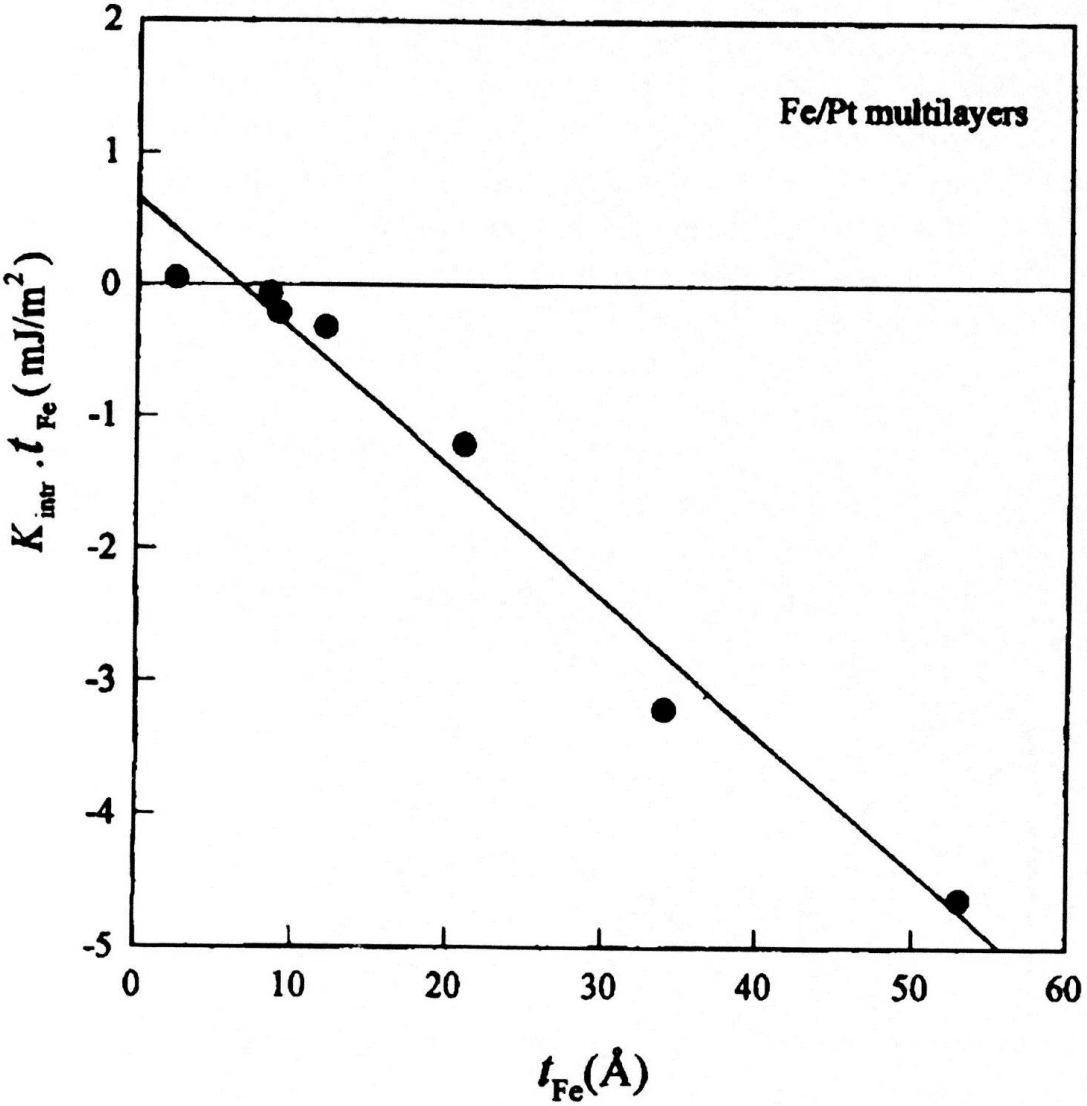

Fig. 5: $t_{Fe}K_{intr}$ as a function of t_{Fe} for the Fe/Pt multilayers.

The surface anisotropy on the magnetocrystalline anisotropy of the transition metal free-monolayers can be understood on the basis of the characteristics of the two sub-bands formed in the in-plane states (IPS) and in the out-of-plane states (OPS). The sign of the anisotropy can then be derived by considering which symmetry states are dominant in the vicinity of the Fermi level (E_F). In the metallic thin films, the OPS cannot form bonds directed towards the surface, then the corresponding sub-band is narrower than that in the bulk. By contrast, the IPS, and be consequence the corresponding sub-band, are essentially unaffected when going from the bulk to the monolayer. In addition, the OPS sub- band is shifted toward higher energy with respect to the IPS sub-band due to the increased electrostatic repulsion for more localized states. Assuming a strong ferromagnetism, only states in the minority band need to be considered. The characteristics of these sub-bands are illustrated in fig. 6, see also in refs. [4,11]. For the low band filling the anisotropy is perpendicular as IPS are dominated. As band filling increases, the contribution of the OPS increases and the anisotropy becomes an in-plane one. For further filling, the anisotropy decreases and vanishes when the band is full. This results

product well the calculation anisotropy reported in [9,13] for the transition metal monolayers: Fe - very weak perpendicular, Co - in-plane and Ni - weakly in-plane. This simple approach can be applied to the interfacial anisotropy of the multilayers by considering the modification of the band structure, and by the consequence of the (effective) band-filling through hybridisation at the interfaces [4]. In this case, as a general rule, one assumes that the IPS do not depend on the nature of the interface and only the OPS are important in this consideration. For the investigated Fe/Pt multilayers, see (fig. 5) above, due to the $3d(Fe)$-$5d(Pt)$ hybridisation the number of the $3d(Fe)$ OPS around the Fermi level is reduced. This tends to favour a perpendicular anisotropy. Moreover, the hybridised Fe-states are fully occupied because they are well below E_F. Thus, the total number of electrons to distribute in the bands which are crossed by E_F is reduced. The total number of states under E_F before hybridisation, however, is relatively less reduced than the number of electrons to distribute. This effect is equivalent to removing some electrons from these bands and this leads to a reinforcement of the interfacial perpendicular anisotropy as observed in this study.

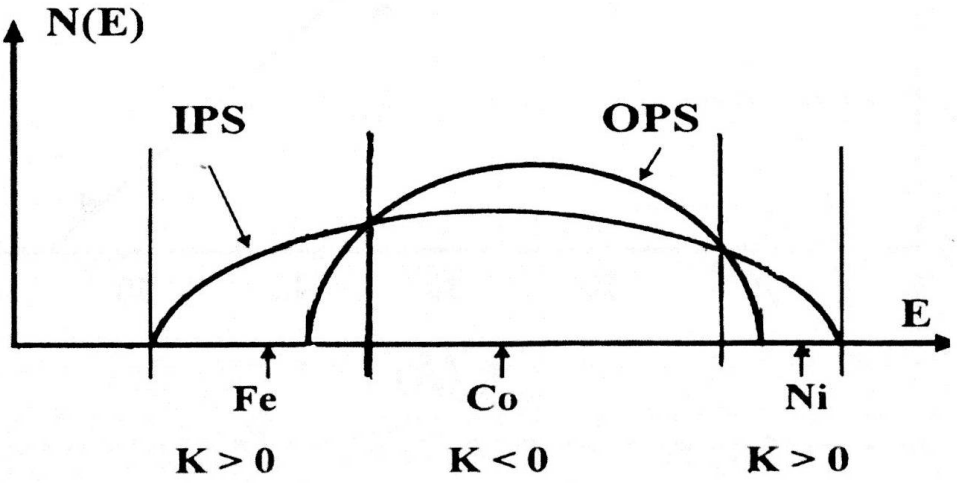

Fig. 6: Schematic illustration of the OPS- and IPS-subbands (see text) and the variation of the sign of the surface anisotropy as a function of band filling. Arrows indicate the position of the Fermi level for Fe, Co and Ni.

IV. CONCLUDING REMARKS

We have presented a study of the interfacial magnetism and anisotropy of Fe/Pt multilayers. Our analysis pointed out that in Fe/Pt interfaces the Fe-magnetic moments and the induced Pt-ones are oriented parallel along the film- normal direction. This leads to a positive contribution to the magnetisation and to the interfacial perpendicular anisotropy in investigated multilayers. We have discussed these behaviours by evoking a simple band structure model and by considering hybridisation effects as proposed by Givord et al. [4]. It appears that this very simple model can be successful in describing the magnetism and anisotropy of Fe/Pt interfaces.

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TẠP CHÍ KHOA HỌC ĐHQGHN, KHTN, t.XV, $n^0$2 - 1999

TỪ TÍNH VÀ DỊ HƯỚNG TỪ CỦA CÁC LỚP CHUYỂN TIẾP (INTERFACES) TRONG CÁC MÀNG MỎNG ĐA LỚP Fe/Pt

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Tính chất từ của các màng mỏng đa lớp Fe/Pt có chiều dày lớp Pt cố định ($t_{Pt} = 15\mathring{A}$) và chiều dày lớp Fe thay đổi ($2.4\mathring{A} \leq t_{Fe} \leq 53\mathring{A}$) đã được nghiên cứu bằng phép đo từ độ ở nhiệt độ phòng sử dụng từ kế mẫu rung (VSM). Các kết quả nhận được cho thấy rằng các vùng chuyển tiếp (interface) của màng được tạo bởi hợp kim của Pt và Fe. Trong các vùng này, mômen từ cảm ứng của Pt sắp xếp song song với mômen từ của Fe và định hướng vuông góc với mặt phẳng của màng. Các thuộc tính này đã được thảo luận dựa trên mô hình lai hoá của các trạng thái $3d(Fe)$ và $5d(Pt)$.