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Magnetic and Magneto-optical Properties of Ni/Pt Multilayers with Perpendicular Magnetic Anisotropy at Room Temperature

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The magnetic and magneto-optical properties of Ni/Pt multilayers exhibiting square Kerr hysterisis loops at room temperature were studied. Squared polar Kerr hysterisis loops at room temperature in Ni/Pt multilayer thin films were obtained for the samples prepared by sequential dc magnetron sputter deposition of nickel and platinum with t_{Ni} = 13 - 21 Å and t_{Pt} = 3.5 - 7.5 Å. The coercivity of these multilayers was in the range of 400 - 1100 Oe. The saturation magnetization was found to show an inverse dependence on nickel sublayer thickness. About a monolayer of Ni at interface was observed to behave less magnetically than the interior Ni atoms. The polar Kerr rotation exhibited an increasing trend with decreasing wavelength in the spectral range of 7000-4000 Å. The maximum of polar Kerr rotation was found to shift to higher wavelengths with increase in nickel sublayer thickness.

1. Introduction

A desirable magneto-optical recording medium should demonstrate perpendicular magnetic anisotropy along with squared Kerr hysterisis loop at ambient temperature, since the remanant Kerr rotation is utilized in the reading process. Multilayers of Co/Pt and Co/Pd which exhibit novel magneto-optical and magnetic properties were found suitable for magneto-optical recording media [1-5] especially for applications with blue laser light. The choice of the sublayer thicknesses dictates these desirable magnetic and magneto-optical properties. In these multilayers, the influence of interfaces of the transition metal in contact with the noble metal has been observed to change the magnetization direction from in-plane to perpendicular to the film. Perpendicular magnetic anisotropy has also been reported in Fe/Pt and Fe/Pd multilayers [6-8] besides cobalt based multilayers. Although there are published reports of observation of perpendicular magnetic anisotropy in Ni/Pt by Krishnan *et al.* [9] and Kielar *et al.* [10], these reports indicate observation of this essential feature at temperatures far below room temperature, about 5 K, which make them unsuitable for any practical application. To the best of our knowledge there are no reports published on Ni/Pt multilayers which exhibited squared hysterisis loops at room temperature. In this paper we discuss in detail our observations in Ni/Pt multilayers, which emphasizes the need to make right choice of sublayer thicknesses based on the knowledge of the effective Curie temperature of the multilayer system and their magnetic and magneto-optical properties are discussed.

2. Experimental

Ni/Pt multilayers with the same number of repeats of 15 were deposited by sequential dc magnetron sputtering on glass substrates under a base pressure of 1×10^{-6} Torr and sputtering argon gas pressure of 7 mTorr. The dwelling time of the substrates above the targets was controlled using a microprocessor-based stepping motor. The substrate-to-target distance was 7.5 cm. Deposition rates of 1 Å/s for Ni, and 3.25 Å/s for Pt, were achieved by applying the same power of 30 W to each of the targets (Ni and Pt). The thickness of platinum was varied from 3.5 Å to 15 Å, while thickness of Ni was varied from 2 Å to 21 Å. Since the onset point for ferromagnetism in NiPt alloys is about 42% of Ni and the Curie temperature shows almost linear dependence on Ni concentration beyond this point and the Curie temperature shows almost linear dependence on Ni concentration beyond this point and the Curie temperatures of thin films are lower than those of their bulk counterparts, we maintained higher Ni sublayer thickness than Pt sublayer thicknesses to obtain the square loops at ambient temperature [11]. Low-angle x-ray diffraction of these multilayers was studied to investigate the integrity of multilayer structure, thickness of the sublayers and total layer, and the details of the interfaces. The low-angle x-ray diffraction patterns of all Ni/Pt multilayers in this study showed peaks characteristic of the multilayer structure. The Kerr loops at 5320 Å and the spectral dependence of the Kerr rotation were measured using a Kerr spectrometer based on a photo-elastic modulator. The magnetizatioin was measured using a vibration sample magnetometer and the magnetic anisotropy was determined using a vibration sample magnetometer and the magnetic anisotropy was determined using a torque magnetometer under an applied field of 10 KOe.

3. Results and Discussion

The transition between in-plane and perpendicular anisotropy is well understood to be due to the competing contribution from interface and volume to the magnetic anisotropy. Relatively thick films have in-plane magnetization due to the volume contribution via the shape anisotropy. The shape anisotropy contribution is proportional to the square of the saturation magnetization, M_s. The saturation magnetizatioin values of Fe, Co and Ni are 1714, 1422, and 484 emu/cc, respectively. Since M_s of Ni is lower than Fe and Co, the shape anisotropy contribution of Ni layer is roughly 9 times lower than Co. Thus, it is reasonable to expect perpendicular magnetic anisotropy at room temperature by optimizing the sublayer thicknesses. Also, due to the reduced volume contribution with respect to Co layer, a much larger range of magnetic layer thickness with perpendicular magnetic anisotropy is expected. The torque measurements of Ni/Pt multilayers used in this study indicated perpendicular magnetic anisotropy in all Ni/Pt multilayers with t_{Pt} upto 7.5 Å and in-plane characteristics beyond this platinum sublayer thickness. Figure 1 illustrates a typical torque vs rotation angle measurement corresponding to (13-Å Ni/3-5 Å Pt) multilayer and (13-Å Ni/8.6-Å Pt). Figure 2 illustrates the dependence of anisotropy energy on nickel sublayer thickness. It can be observed from Fib. 2 that the anisotropy energy decreases monotonically with increasing nickel sublayer thickness from 13 Å to 21 Å. We have also observed that the anisotropy energy decreases with increasing platinum sublayer thickness. The decrease in anisotropy with increasing platinum thickness could be due to (a) increased interface roughness due to more exposure to backscattered heavier mass Pt atoms during deposition,

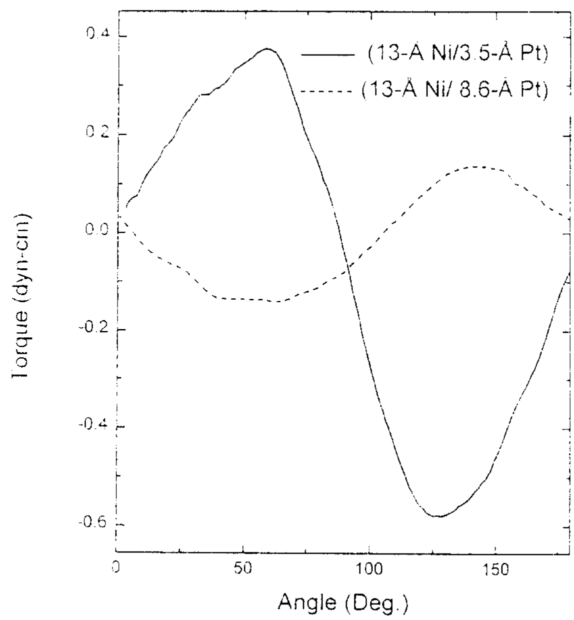

Figure 1. Typical torque curves of Ni/Pt multilayers corresponding to $(13\text{-Å Ni}/3.5\text{-Å Pt})_{15}$, and $(13\text{-Å Ni}/8.6\text{-Å Pt})_{15}$.

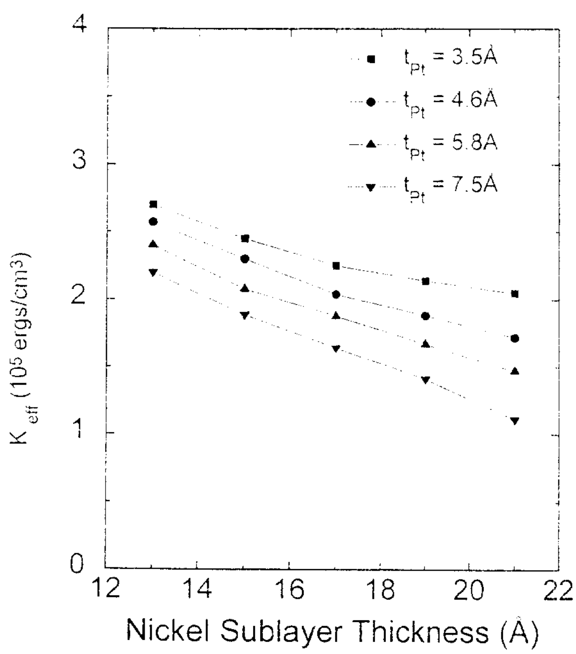

Figure 2. Dependence of the anisotropy energy on nickel sublayer thickness in Ni/Pt multilayers

(b) drastic decrease in T_C of Ni/Pt multilayers, and (c) changes in the nature and magnitude of stress. The decrease in anisotropy with increasing nickel sublayer thickness is attributed to an increase in demagnetization energy and changes in magnetocrystalline and magneto-elastic anisotropies. The magnetic anisotropy of (Ni/Pt) multilayers can be described phenomenologically as

$K_{eff} = K_V + 2(K_S^{Ni/Pt}/t_{Ni})$

where the subscript 'v' and 's' refer to the volume and surface contributions to anisotropy, respectively. The intercept of the straight line plot of $K_{eff}t_{Ni}$ vs t_{Ni} is twice the surface anisotropy which is observed to be positive but smaller than that is reported for Co-based multilayers [8] and also, the volume anisotropy as determined from the slope was found to be positive indicating that the both surface anisotropy and volume anisotropy contribute to perpendicular magnetic anisotropy. The positive volume anisotropy observed is consistent with the preferential orientation of Ni (111), an easy axis perpendicular to the film [12]. The surface anisotropy as estimated was about 0.001 ergs/cm^2. The small $|K_s|$ observed may be due to the cancellation effect of Neel interface ansotropy and interface misfit dislocation anisotropy resulting from strain at the interface as usually observed in incoherent multilayer structures [8]. In the case of Ni/Pt multilayers the critical thickness for an coherent to incoherent transition was calculated to be about 1.2 Å. The magnetocrystalline anisotropy for bulk Ni which is K_C = 4.5 x 10^4 ergs/cm^3 and the difference in lattice spacing between Ni and Pt of about 10.2% are expected to contribute to the magnetic anisotropy. Krishnan *et al.* have reported that the intrinsic anisotropy in Ni/Pt multilayers arises only from the magnetoelastic interactions [13]. Detailed study on the anisotropy in Ni/Pt multilayers which includes in-situ stress measurements, magnetostriction measurements and the dependence of anisotropy on number of multilayer repeats are being carried out to identify the individual contributions to the volume anisotropy and shall be reported elsewhere.

The minimum thickness of Ni sublayer for which the Kerr hysterisis loop could be observed was 9 Å. We have observed the Kerr loops wit the loop squareness of unity for multilayers with t_{Ni} = 13 to 21 Å and t_{Pt} = 3.5 Å. Figure 3 illustrates the typical polar Kerr rotation loops of Ni/Pt multilayers corresponding to (15-Å Ni/3.5-Å Pt)$_{15}$, (17-Å Ni/3.5-Å Pt)$_{15}$, and (19-Å Ni/3.5-Å Pt)$_{15}$. Except in the case when t_{Pt} was about 3.5 Å, the loop squareness decreased with increasing the nickel sublayer thickness for the same platinum sublayer thickness, which was consistent with torque magnetometric measurements exhibiting a decrease in total anisotropy with Ni sublayer thickness. We also observed that the loop squareness ratio decreased with increasing the platinum sublayer thickness for same nickel sublayer thickness. This is due to the decrease in the Curie temperature (and therefore, magnetization), and the associated changes in anisotropy with increasing t_{Pt} for same t_{Ni} in Ni/Pt multilayers. Krishnan *et al.* in the first ever report on Ni/Pt multilayers reported rectangular loops for $t_{Ni} \le 10.5$ Å and t_{Pt} = 20 Å at 5 K far below room temperature. For $t_{Ni} \ge 3.3$ Å, they have reported that in-plane M-H loops are rectangular with high remanence ratio indicating that easy axis lies in the film plane. And as the temperature is decreased remanance ratio for in-plane M-H loops is reported to decrease and M-H loops along the film normal exhibited some remanance [9]. Krishnan *et al.* in another article have reported that Ni/Pt multilayers with t_{Ni} < 1.5 nm exhibited distinctly different behavior from those with thicker nickel layers [13]. Figure 4 illustrates the dependence of the coercivity on nickel sublayer thickness. Higher coercivity values were observed when the thickness of platinum sublayer was 3.5 Å. In general the coercivity

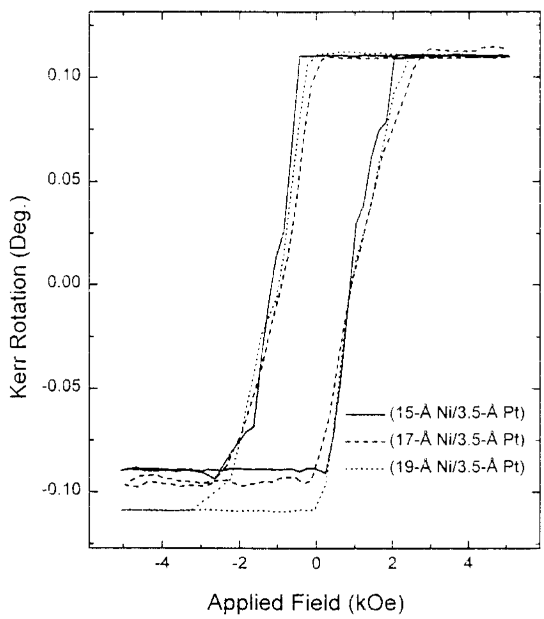

Fig.3. Typical polar Kerr hysterisis loops of Ni/Pt multilayers corresponding to (15-Å Ni/3.5-Å Pt)$_{15}$, (17-Å Ni/3.5-Å Pt)$_{15}$, and (19-Å Ni/3.5-Å Pt)$_{15}$.

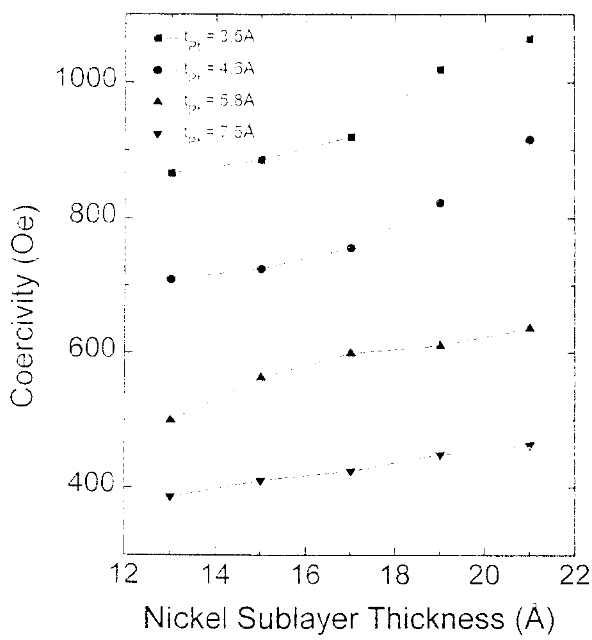

Fig.4. Dependence of the coercivity on nickel sublayer thickness in Ni/Pt multilayers.

showed an increasing trend with increasing nickel sublayer thickness. According to Kronmüller *et al.*, the coercivity H_C is given by [14]

$$H_C = 2\alpha K_u/M_s - N_{eff}M_s$$

where α is a parameter responsible for microstructure determined by coupling strength between wall and wall pinning sites, N_{eff} is the demagnetization factor, which consists of the macroscopic and microscopic demagnetizing effects. The macroscopic factor is related to sample geometry while the microscopic one to the size and type of pinning site (magnetic/nonmagnetic). The increasing trend of the coercivity with increasing nickel sublayer thickness can be ascribed to an increase in magnetocrystalline anisotropy as reflected by an increasing trend of the (111) multilayer diffraction peak and a decreasing trend of the full width at half maxima of the diffraction peak. Another source for this observation could be a change in the demagnetization factor due to change in interface roughness as was observed in Co/Pt multilayers by Suzuki *et al.*[15]. We also observed that the coercivity decreased with increasing the platinum sublayer thickness for same nickel sublayer thickness. This is due to the decrease in the Curie temperature and the associated changes in anisotropy with increasing t_{Pt} for same t_{Ni}: it was observed that the Curie temperatures of the samples showing perpendicular magnetic anisotropy were varied between 178 - 258 °C with increasing trend for a higher Ni concentration. Figure 5 illustrates the dependence of the saturation magnetization on nickel sublayer thickness. It can be observed from Fig. 5 that as expected, M_s increases with increasing t_{Ni} and decrease with increasing t_{Pt}. The decrease in Ms with increasing the platinum sublayer thickness for same nickel sublayer thickness is due to the decrease in the Curie temperature. It can be observed from Fig. 5 that the magnetization per unit volume of Ni in Ni/Pt multilayers are lower than that of bulk value of nickel, 480 emu/cc. This reduction in the magnetization can be due to higher density of defects and greater interfacial roughness, due to large expansion of magnetic material lattice (due to lattice mismatch) leading to significant concentration of dislocations or as often associated with speculation that certain thickness of Ni at each interface is behaving nonmagnetically or less magnetic while the interior Ni atoms retain their full moments. We have observed a $1/t_{Ni}$ dependence of the magnetization strongly indicating the interfacial effects. The proximity of a nonmagnetic metal is observed to suppress the magnetic moment of some elements depending on the extent of overlap of magnetic metal's d-band and nonmagnetic metal's conduction band wavefunctions. Tersoff *et al.* [16] in a study of magnetic and electronic properties of Ni films, surfaces and interfaces, concluded that increased sp-d hybridization when a Ni atom is adjacent to noble or normal-metal atoms leads to suppression of Ni magnetization. Chubing *et al.* [12] in a study on Ag/Ni multilayers also observed lower magnetization of interface Ni sublayer than that of inside Ni layers due to diffusion and charge transfer from Ag atoms to Ni 3d band near Ag/Ni interface. It is important to note that Hanson *et al.*[17] in a study of magnetization and microstructure of dc magnetron sputtered Ni films observed that the saturation magnetization of Ni films was always lower than that of bulk in films deposited at room temperature. The thickness of this nonmagnetic or less magnetic layer at each interface could be estimated using the phenomenological relation, $M = M_0\,(1\text{-}2\ \delta/t)$, where M is the multilayer magnetization, M_0 is the magnetization of bulk Ni, δ is the thickness of nonmagnetic layer and t is the thickness of magnetic layer. Estimation from our result indicated that the thickness of nonmagnetic or less magnetic nickel sublayer was about a monolayer which was similar to that predicted by Krishnan *et al.*[13]. The observation of less magnetic or magnetically dead interfaces was consistent with our anisotropy measurements which indicated that the surface anisotropy is negligible and the volume anisotropy is the major source of perpendicular magnetic anisotropy in Ni/Pt multilayers.

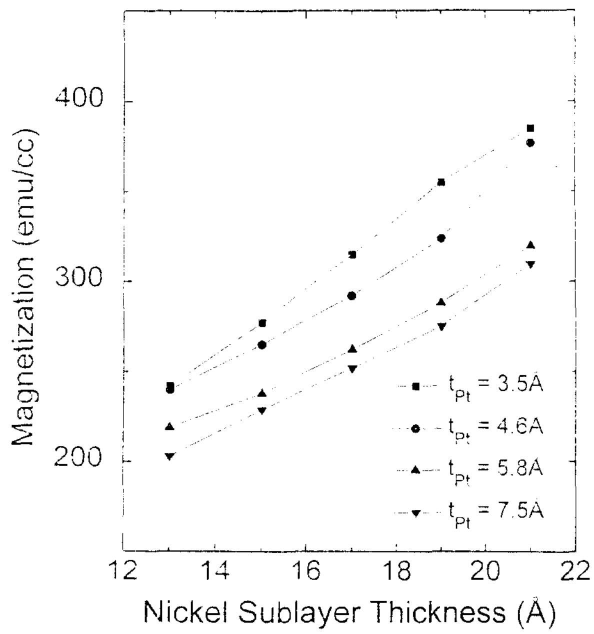

Fig. 5 The dependence of magnetization on nickel sublayer thickness in Ni/Pt multilayers

Figure 6 illustrates the typical spectral dependence of Kerr rotation of Ni/Pt multilayers corresponding to (15-Å Ni/3.5-Å $Pt)_{15}$, (17-Å Ni/3.5-Å $Pt)_{15}$, and (19-Å Ni/3.5-Å $Pt)_{15}$, measured in a magnetic field of 5 kOe sufficient to saturate samples perpendicular to the film. The magnetic field required for saturation was estimated from Kerr hysterisis loops. The Kerr spectra of sputtered Ni film of 600-Å thickness is also shown in Fig. 6 for comparison. It is important to note that the Kerr spectrum of pure nickel exhibits maxima around 1.6 eV (about 7700 Å) and 3.25

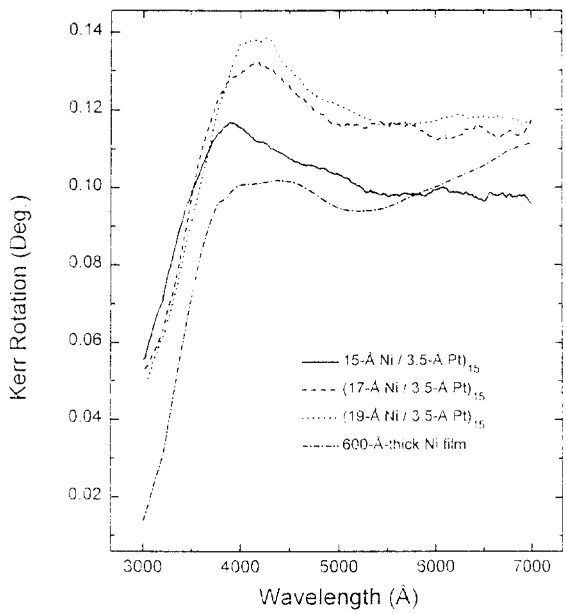

Fig.6. Typical Kerr spectra of Ni/Pt multilayers corresponding to (15-Å Ni/3.5-Å Pt)$_{15}$, (17-Å Ni/3.5-Å Pt)$_{15}$, and (19-Å Ni/3.5-Å Pt)$_{15}$

eV (about 3800 Å), also the Kerr spectrum of Ni shows a change of sign near 0.9 eV (about 13500 Å) and again at 4.1 eV (about 3000 Å)[18]. The enhancement of Kerr rotation in the Ni/Pt multilayers as compared to the Ni-film is believed to be from the optical enhancement due to the thinner multilayer thickness than the pure Ni film rather than from any intrinsic properties. The Kerr rotation was observed to increase with increasing t_{Ni}, in most of the spectral range as expected, which is consistent with the magnetization measurements. We have also observed that the maxima in Kerr rotation shifts to higher wavelengths with increase in t_{Ni}. The Kerr rotation was observed to decrease with increase in t_{Pt} due to a reduction in the Curie temperature and therefore the magnetization. Krishnan *et al.* [19] and Visnovsky *et al.* [20] reported similar observation of magneto-optical enhancement in the near UV region, peak shifts to higher energies (lower wavelengths) with decreasing nickel sublayer thickness and a change of sign at about 4 eV (about 3100 Å) for all Ni/Pt multilayers.

4. Conclusions

In conclusion, Ni/Pt multilayers exhibiting perfectly squared polar Kerr hysterisis loops with high coercivity, substantial magnetization, and Kerr rotation were prepared by suitable choice of sublayer thickness. These multilayers with sensitive magneto-optical and magnetic properties are attractive for magneto-optical media applications.

Acknowledgements

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