Magnetic Properties of Ni/Pt(111) Thin Film Studied by MOKE

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Magnetic anisotropies and the Curie temperature of a Ni thin film were studied by the magneto-optic Kerr effect. A Ni thin film of thickness of 150 Å was vapor deposited on a Pt(111) surface. Some improvements for detecting the Kerr signal are discussed. From the hysteresis loops of the thin film we found that the in-plane anisotropy is uniaxial. The direction of this uniaxial anisotropy was identified. The Curie temperature of this thin film is 580 K. Magnetization as a function of temperature was studied.

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The magneto-optic widely used to study magnetic properties of ferromagnetic thin films, such as magnetic anisotropy, surface Curie temperatures, and magnetic domains related to surface structures or as functions of thickness [12]. It is a relatively simple and inexpensive technique. Furthermore, it can be used to study surface magnetism of ultrathin films, by the so called SMOKE can be used to measure magnetic hysteresis curve with sensitivity within a monolayer range. Recently, some inter-

II. Experimental

The pressure within the UHV chamber was measured by an ion gauge and checked by a quadrupole mass spectrometer. The UHV chamber was also equipped with low-energy electron diffraction (LEED), Auger electron spectroscopy (AES) and ultraviolet photoelectron spectroscopy (UPS). The...
determined by X-ray diffraction. The Pt(111) substrate was cleaned by cycles of argon ion bombardment and annealing until sharp diffraction spots with low background were

A Ni coil of 0.5 mm in diameter and 99.997% in purity was evaporated to form a thin film with thickness of 150 Å at a rate of 0.9 Å per minute. The thickness of the thin film was measured by a thickness monitor and calibrated by AES. The Pt substrate was kept at the room temperature during the deposition. The background pressure was about 1 × 10⁻⁶ Torr during Ni dosing. For maintaining high purity of Ni adlayers, the Ni coil was pre-heated a few minutes before the deposition. The temperature of the sample was measured by a k-type thermocouple.

Magnetic properties of this thin film system were studied by the MOKE technique. A schematic figure of the experimental arrangement is shown in Fig. 1. A He-Ne laser with a wavelength of 6328 Å and an output power of 5 mW was used as the light source. A linear polarizer of Glan-Thompson polarizing prism polarized incident light with an extinction ratio of 1 × 10⁻⁶. The direction of polarization of laser light can be chosen either in the incident plane (p-polarized) or normal to the incident plane (s-polarized). The p-polarized wave was chosen in this experiment. An aperture is used to avoid halo of light. After reflecting from the sample surface, the light passes through a quarter-wave plate. It can produce a π/2 phase shift of incident light which interconverts Kerr rotation and Kerr ellipticity [8]. The Kerr signal, obtained in this experiment, is Kerr ellipticity. An analyzing polarizer of Wollaston polarizing prism can separate reflected light to p-polarized and s-polarized components. This helps us to read the Kerr signal more precisely when we

![FIG. 1. A schematic representation of the MOKE setup.](image-url)
only measured the s-polarized component of the reflected beam after the Kerr rotation. The reason is that the ratio of the change of the intensity to its original intensity of the s-polarized component, \( AI/I \), is much stronger than that of the p-polarized component in our experimental arrangement. The use of this polarizing prism is important in MOKE according to our experience. The Kerr signal was detected by a photodiode and recorded as a function of the applied magnetic field \( H \) to generate the hysteresis loop. A computer was used to record hysteresis curves. The maximum magnetic field \( H \) can be up to 1410 Oe in our system.

The first improvement for MOKE studying is the use of the laser intensity stabilizer of THORLABS. It is a feedback system which regulates the intensity of a laser beam and improves the signal-noise ratio for the weak MOKE signal [9]. The second is that we detected the change of the intensity to original intensity, \( AI/I \), instead of \( AI \). This normalized process reduces the fluctuation of the Kerr signal. Moreover, the photodiode of ONSET (ET 4000) used in this study has a large active area up to 20 mm\(^2\). This large active area removes the need for focusing optics and minimizes the problems associated with the stability of the optical path.

### III. Results and discussion

The morphology and structure of the Ni thin film was examined by LEED and X-ray diffraction. The intensity of the LEED spots decreases and the background grows monotonously as the thickness of Ni increases. The LEED pattern is still in 3-fold symmetry up to Ni thickness of 150 Å, but the LEED spots are more diffused at higher thicknesses. It indicates that the surface morphology is rougher than the original Pt substrate. This may result from the lattice match between Ni and Pt atoms. X-ray diffraction pattern for 150 Å Ni thin film is also in S-fold symmetry and the diffraction spots is along the crystal axis of the substrate. So we can conclude that the Ni thin film is single crystalline and epitaxial.

There are three configurations in MOKE: polar MOKE, longitudinal MOKE and transverse MOKE. These terms correspond to orientation of the magnetization with respect to the scattering geometry. In the polar MOKE, the direction of magnetization is along the surface normal. In the longitudinal MOKE, the direction of magnetization is in the sample surface and in the incident plane. In the transverse MOKE, the direction of magnetization is also in the sample surface but perpendicular to the incident plane. Because the transverse Kerr effect has a small change in reflectivity for p-polarized light [10], the magnetic properties of this thin film were examined by the polar MOKE and the longitudinal MOKE only in our experiment. The in-plane easy axis and hard axis were determined by measuring the longitudinal MOKE at varying azimuthal angles.

Fig. 2 shows the hysteresis loop of the Ni thin film by the polar MOKE in which the applied magnetic field \( H \) is perpendicular to the film plane. We measured the intensities of Kerr ellipticities, which are proportional to the magnetization of the Ni/Pt(111) thin film, as a function of applied magnetic field to generate the hysteresis curve. One can find that the shape of the hysteresis loop is long and thin. The magnetization is still not in saturation as the applying field reaches a maximum value of 1410 Oe. Both the remanence and the coercive force are very small. So we conclude that the hard axis of magnetization of this system is perpendicular to the sample surface. This is as we expect, because the
FIG. 2. The hysteresis loop of the Ni/Pt(111) thin film measured by the polar MOKE. The applied magnetic field was directed along the normal of the specimen. The shape of the hysteresis loop is long and thin. The magnetization is not saturated at maximum $H=1410$ Oe. The remanence and the coercive force are small. This hysteresis loop shows that the hard axis of magnetization is perpendicular to the surface normal.

demagnetizing field contribution favors as in-plane orientation for the magnetization rather than a perpendicular one.

It is interesting to examine the in-plane anisotropy of this thin film after we confirmed that the magnetization favors lying in the sample plane. The longitudinal MOKE was used to search for the easy axis in the sample plane. Since the Kerr ellipticities are proportional to the magnetization projected onto the propagation vector of light in the magnetic material [11], a larger incident angle can increase the Kerr ellipticity in the longitudinal MOKE. A $45^\circ$ incident angle was taken in this experiment. The range of the external field was varied from -1410 to 1410 Oe. We rotated the sample about the axis of the surface normal to vary the azimuthal angle $\phi$. A series of hysteresis loops were obtained at different azimuthal angles as shown in Fig. 3. The shape of the hysteresis loop at $\phi=0^\circ$ (Fig. 3(a)) is close to a rectangle and seems to exist in two states only. The magnetization is saturated at $H_s=675$ Oe and still keeps in saturation as the external magnetic field decreases from 1410 Oe to -150 Oe. The coercive force is 375 Oe. Comparing with other hysteresis loops in Fig. 3, the value of $H_s$ at $\phi=0^\circ$ is the smallest, but the coercive force and the remanence are the largest. These are the evidence of the easy axis of magnetization [12].

As $\phi$ increases from $0^\circ$ to $90^\circ$ (Fig. 3 (b)-(d)), the hysteresis loops change to thinner in shape and corresponding $H_s$ becomes larger gradually. The shape of the hysteresis loop also changes from a rectangle to a smooth curve. In addition, $H_s$ is the largest and the coercive force and the remanence are the smallest at $\phi=90^\circ$. This represents that the axis along $\phi=90^\circ$ is the relative hard axis of magnetization in the thin film plane. The hysteresis loop at $\phi=180^\circ$ (Fig. 3(g)) is identical to that of $\phi=0^\circ$. We examined all hysteresis curves and found that the hysteresis loops within $180^\circ<\phi<360^\circ$ are similar to
FIG. 3. The hysteresis loops of the Ni thin film measured by the longitudinal MOKE at different azimuthal angles $\varphi$: (a) $0^\circ$, (b) $30^\circ$, (c) $60^\circ$, (d) $90^\circ$, (e) $120^\circ$, (f) $150^\circ$, (g) $180^\circ$.

FIG. 4. The atomic structure and the coordinate of a Pt(111) surface. The in-plane easy axis of magnetization is along $[1,1,-2]$.

those within $0^\circ < \varphi < 180^\circ$ correspondingly. In other words, hysteresis loops are repeated after the azimuthal angle $\varphi$ rotates $180^\circ$. This means that it has an in-plane uniaxial magnetic anisotropy of this thin film. The easy axis of magnetization is in the direction of $\varphi = 0^\circ$. We used an X-ray diffraction technique to identify this easy axis and confirmed that it is along the $[1,1,-2]$ direction of the substrate. This means that the easy axis is along the direction of the next nearest neighbor of atoms and perpendicular to the $[1,-1,0]$ as shown in Fig. 4.

It is surprising that the magnetic anisotropy is in a 2-fold symmetry in the thin film plane and is not in a 3-fold symmetry like that of the Pt(111). According to a study of Ni thin films on CuSn$_6$ substrate, the direction of the in-plane easy axis of the Ni thin film is strongly influenced by stress [13]. Recently it was pointed out by Albrecht et al. [14] that micro-structures at the surface, like steps, should give rise to additional magnetic surface anisotropies. Mulfhekel et al. [15] found that the uniaxial component is dominant and the easy axis of magnetization is parallel to the step edges. The physical reasons of the uniaxial anisotropy in this system need further study. The most possibility of the symmetry broken is the high-energy ion sputtering at an incident angle of 45 degree in the surface cleaning.
process. The kinetic energy of Ar ion bombardment was about 2.2 keV. Some surface steps were induced in the inclined sputtering and annealing cycles. We can express the magnetic anisotropy of the Ni thin film as the sum of a threefold in-plane anisotropy term $K_1$ and a uniaxial anisotropy term $K_u$, i.e., $K = K_1 + K_u$, and $K_u$ is dominant. This in-plane magnetic uniaxial anisotropy is also found in a Co/Cu(100) thin film system [16].

The change of hysteresis loops of the easy axis as a function of temperatures is shown in Fig. 5. The Kerr ellipticity which corresponds to magnetization decreases monotonously as the temperature increases. The coercive force and the remanence also decrease as the temperature increases. These changes come from the thermal fluctuation of magnetic domains. The Kerr ellipticity becomes very weak at $T=570$ K. The remanent magnetization is very small at this temperature. The Curie temperature of this thin film must be slightly higher than this temperature.

The evolution of Kerr ellipticity as a function of the temperature is shown in Fig. 6 for a Ni(111) single crystal and the Ni/Pt(111) thin film. The single crystal disk of Ni(111) was served as a comparison. The applied magnetic field was 1410 Oe. The intensity of Kerr ellipticity for the Ni(111) single crystal in curve A decreases as the temperature increases. But it drops to zero slowly as the temperature is close to 610 K. It approaches to zero at 625 K. This means that the Curie temperature of the bulk Ni(111) is 625 K. This value agrees with the published value of 627 K measured by other techniques within the experimental error [17]. The intensity of the Kerr ellipticity for the Ni/Pt(111) thin film is smaller than that of the bulk Ni(111), because the intensity of the Kerr ellipticity is proportional to the thickness of a magnetic thin film [10]. The noise of the Kerr ellipticity due to thermal fluctuation of this thin film is much larger than that of the bulk Ni. We measured the intensity of Kerr ellipticity 2000 times within 5 minutes at each temperature. The average value and the standard deviation of each data point are shown in the curve B (Fig. 6). The Kerr signal of the Ni/Pt(111) thin film approaches to zero at 585 K. It is lower than that of the bulk Ni. This result is as we expect since the Curie temperature for a film is usually reduced from that for the bulk [4,18].

One can find a small tail in the vicinity of the Curie temperature on the curve of Fig. 6. Some authors suggested that the small tail is indicative that the film is not infinite in two dimensions [19]. It is also possible a superparamagnetic response [20]. In a superparamagnet small grains or islands behave as paramagnetic particles with a huge magnetic moment. However the small tail occurs at temperatures slightly above the real Curie temperature ($T_C$) and the magnetic thin film is almost in the paramagnetic state [19,21]. The Curie temperature determined by MOKE is the extrapolated limit at which the remanent magnetization in the direction of the easy axis goes to zero. Therefore, one has to drop the tail part and let the remanent magnetization vanishes sharply to identify $T_C$ more accurately. After correction, the Curie temperature of the Ni/Pt(111) thin film is 580 K.

IV. Conclusion

A 150 Å Ni thin film was deposited by vapor deposition on a Pt(111) surface. The polar and longitudinal MOKE were used to study its magnetic anisotropies. The hard axis of magnetization is along the surface normal. The easy axis of magnetization is along the
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FIG. 5. Hysteresis loops of the in-plane easy axis change as a function of temperatures: (a) 300 K, (b) 370 K, (c) 425 K, (d) 480 K, (e) 530 K, (f) 570 K.

FIG. 6. The evolution of Kerr ellipticity as a function of annealing temperature for a Ni(111) single crystal (curve A), and the Ni/Pt(111) thin film (curve B). The applied magnetic field was 1410 Oe. The Curie temperatures for the Ni(111) single crystal and the Ni/Pt(111) thin film are 625 K and 580 K, respectively.

[1,1,-2] direction of the substrate surface. The in-plane anisotropy is uniaxial. The possible mechanism of the in-plane anisotropy is discussed. The Curie temperature of the Ni/Pt(111) thin film is 580 K.

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References