Development of an UHV-SMOKE System Using Permanent Magnets

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(Received 19 April 2010; Accepted 10 May 2010; Published 12 June 2010)

We have developed an ultra-high-vacuum surface-magneto-optical Kerr effect (UHV-SMOKE) system which utilizes a pair of Sm-Co permanent magnets to apply magnetic field as large as ±0.23 T. The magnetic field can be applied parallel and perpendicular to the sample surface to perform longitudinal and polar Kerr effect measurements, respectively. The field strength can be changed by rotating the magnet pair symmetrically. The system can be operated in the vacuum of ~10⁻¹¹ Torr and at the temperature as low as ~20 K. We have adopted the Faraday-cell modulation technique to obtain the detection sensitivity of Kerr rotation angle as small as 10⁻⁴ degree. Its capability is demonstrated by measuring the hysteresis loops of Co layers deposited on Ag(111) film.

Keywords: Surface-magneto-optical Kerr effect; SMOKE; Hysteresis loop

I. INTRODUCTION

The introduction of magnetic impurities into metals produces exotic phenomena such as Kondo effect [1] and RKKY interaction [2], and has been studied extensively due to its importance not only in terms of fundamental physics but also in application to spin-based electronics. The widely-known III-V bulk semiconductors such as GaAs were shown to become ferromagnetic by doping small amounts of Mn, the so-called diluted magnetic semiconductor (DMS) [3]. By reducing the dimension of the system, the effects of impurities are expected to increase due to the weakened screening effect. Magnetic atom adsorption on low-dimensional systems formed on crystal surfaces have been studied by scanning tunneling spectroscopy (STS) and their local magnetic properties have been characterized [4]. However, there are only a few works that discuss the macroscopic magnetic properties at the surface that are induced by such magnetic impurities [5]. It is well known that metallic surface superstructures formed on semiconductor crystals have electronic states that are decoupled from those of the bulk at the Fermi level. Therefore it is highly intriguing if we can make diluted magnetic systems on semiconductor surfaces that show magnetic properties only at the surface.

In view of this point, it is necessary to characterize the magnetic property at the surface properly. X-ray magnetic circular dicroism (XMCD) has been one of the most powerful methods to investigate surface magnetism [6]. It has the advantages that it has elemental sensitivity, and furthermore, it is capable of obtaining the orbital and spin magnetic moments separately using the sum rule [7]. However, synchrotron radiation with high brilliance is needed and the time to perform experiments and sensitivity to tiny amounts of adsorbates may be limited. Surface magneto-optical Kerr effect (SMOKE) measurement [8] is an alternative to XMCD. Although it lacks elemental sensitivity, it can be performed in laboratory using lasers or conventional light sources. By making slight modifications, other methods such as the Faraday rotation [9] or magnetization-induced second-harmonic generation measurements can be also performed [10].

Among the methods to apply magnetic field in a ultra-high vacuum (UHV)-SMOKE system, superconducting or normal coils have been widely used. Although magnetic fields as high as several Tesla can be achieved by superconducting coils, it is necessary to cool the coils and it is somewhat expensive. Normal-metal coils are cheaper and easier to operate, but the joule heating of the coils sometimes deteriorates the vacuum condition so that the lifetime of the sample surfaces becomes short. This can even prevent one from applying large magnetic fields. Furthermore, in both cases if you want to apply the magnetic field in various directions with respect to the sample surface, several pairs of coils are required inside/outside the UHV chamber, which may make the system quite complicated [11].

In this article, we describe the development of a convenient UHV-SMOKE system which adopts a completely different method to apply the magnetic field with changing the direction and strength. We put a pair of samarium-cobalt (Sm-Co) permanent magnets close to the sample inside the chamber. By changing the angle between the magnets symmetrically, the strength of the magnetic field at the sample position can be changed. The largest magnetic field that we could reach was ±0.23 T, which is comparable to the largest fields obtained using normal-metal coils. The magnet pair was rotated as a whole around the sample to change the field direction with respect to the sample. The system could be operated in the vacuum of ~10⁻¹¹ Torr and at the temperature as low as ~20 K. Our measurement is based on the Faraday-cell modulation method with lock-in technique. We have demonstrated its sensitivity of Kerr rotation angle on the order of 100 μdeg., and its capability by measuring the hysteresis loops of an Co bi-layer deposited on Ag(111)

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FIG. 1: (a) The photo and (b) the schematic drawing of our UHV-SMOKE system. (c) The close-up photograph of the sample sandwiched between magnetic poles and radiated by a He-Ne laser. (d) The plan-view photo of the magnet stage, showing the rotation of the magnet to change the field strength. (e) Its illustration, showing the rotation of the whole stage to change the magnetic field direction.

II. INSTRUMENTAL SETUP

Figures 1(a)(b) show the photo and the schematic drawing of our UHV-SMOKE system, respectively. The whole system is set on a vibration isolator to reduce the influence of the external mechanical vibration. The main chamber has a reflection high-energy diffraction (RHEED) system with evaporation sources to prepare and check the surface structure and layer growth. The sample is prepared at the upper level in the chamber and transferred to the lower level by a z-axis manipulator for the SMOKE measurements. The typical base pressure achieved in this system is in the mid \(10^{-11}\) Torr. Furthermore, the manipulator has a cryostat which enables cooling the sample by flowing cryogen. The main chamber is equipped with a small chamber for fast-entry load-lock, partitioned by a gate valve, to exchange samples.

Now let us describe the method to apply the magnetic field in this system. Figure 1(c) shows the close-up photo of the sample sandwiched between magnetic poles and radiated by a He-Ne laser (\(\lambda=632.7\) nm). The angle of incidence of the laser beam is 45° off the surface normal. Two Sm-Co magnets are placed next to the magnetic poles. When we consider the magnetic flux and symmetrical arrangement, the field in this configuration is parallel to the sample surface and enables longitudinal Kerr effect measurements. The strength of the magnetic field can be changed by rotating the two magnets simultaneously with one of the rotational feedthroughs at the bottom of the main chamber (Fig. 1(b)). Figure 1(d) shows the photograph of the magnet stage on which the two magnets rotate in opposite directions synchronously (clockwise for the left magnet and counterclockwise for the right magnet). The magnets are controlled by a stepping motor.

As shown in Fig. 1(e), the direction of the magnetic field can be changed by rotating the whole stage on which the magnets are placed, with another rotational feedthrough at the bottom of the chamber as shown in Fig. 1(b). This enables one to apply the magnetic field perpendicular to the surface and perform polar Kerr effect measurements.

Figures 2(a)-(c) shows the calculated distribution of magnetic lines of force around the sample, obtained by solving Poisson equation by assuming a pair of dipoles mimicking the magnet pair. Due to the symmetry of the system, the field has x-component only at the center position at any rotation angle of magnets. The solid curve of Fig. 2(d) shows the calculated field strength at the center as a function of rotation angle of the magnet pair. By placing a gauss-meter in the sample position in our apparatus, on the other hand, we measured the field strength with rotating the magnets. The results are shown by solid circles in Fig. 2(d). The field changes almost linearly with the angle. The maximum field is \(0.23\) T, and the field is zero when the two magnets are perpendicular to the magnetic poles. Slight difference is noticed between the calculated and measured ones. This may be because we did not consider the magnetic poles in the calculation.

Figures 2(e) shows the evolution of the sample temperature measured by a Si-diode thermometer attached close to the sample when liquid nitrogen or liquid helium was made flow as cryogen, respectively. We can see that the
FIG. 2: (a)-(c) Simulation results of magnetic lines of force with rotation of the pair of dipoles mimicking the permanent magnets. (d) The measured magnetic field (filled circles) at the sample position and the calculated field (solid line) as a function of the rotation angle of magnet pair. (e) The evolution of the sample temperature when cooled down with liquid nitrogen and liquid helium.

FIG. 3: The close-up photograph of the Kerr effect measurement system with the laser, Faraday-cell, and photodiode (a), and the block diagram of the measurement (b).

The sample can be cooled to \( \sim 82 \) K after 30 minutes and \( \sim 21 \) K after 40 minutes by liquid nitrogen and helium, respectively. The stability of the sample temperature is important for a reliable SMOKE measurement. At the saturation temperatures written above, we were able to reduce the signal-to-noise ratio to a satisfactory level to attain the high resolution in Kerr-rotation angle detection.

There are several types of methods to enhance the detection sensitivity of Kerr rotation angle, such as the spinning analyzer technique [12] or the piezoelectric modulation (PEM) [13]. In our system, we have employed the Faraday-cell modulation method [14, 15], which monitors the DC current in the Faraday-cell for compensating the Kerr rotation angle by the sample. Figure 3(a) shows the close-up photograph of the Kerr effect measurement system and Fig. 3(b) shows the block diagram. The two polarimeters at the light incidence and detection sides are tuned so that their polarization angles are perpendicular to each other and there is practically no intensity detected at the photo-detector. When the polarization angle of the light reflected by the sample is rotated by the Kerr effect, finite intensity is detected at the photodiode. Then we counteract the Kerr rotation by adjusting the current flowing in the Faraday-cell so that again the polarizations of the reflected light is at right angles to the polarimeter in front of the photodiode to zero intensity detected. To increase the sensitivity, an AC current is used as a modulation and overlapped on the DC current in the Faraday-cell \( (i = i_0 + \Delta i \sin \omega t) \). And we use a lock-in amplifier to detect the very weak signal from the photodiode, and adjust the DC current using a feedback controller to attain the zero intensity at the photodiode. Mathematically, the polarization angle of the incident light is expressed as:

\[
\theta = \theta_0 + \Delta \theta \sin \omega t,
\]

where \( \theta_0 \) is the DC component and \( \Delta \theta \) is the amplitude due to the AC current with the frequency \( \omega \). Writing the polarization angle of the reflected light as \( \theta_F \) and the intensity of the incident light as \( I_0 \), the intensity at the detector \( I \) can be written as:

\[
I = I_0 \sin^2(\theta_0 + \Delta \theta \sin \omega t - \theta_F),
\]
which is approximated as

\[ I \approx I_0/2(1 - \cos(2(\theta_0 - \theta_F))J_0(2\Delta\theta)) \\
+ I_0 \sin(2(\theta_0 - \theta_F))J_1(2\Delta\theta) \sin \omega t \\
- I_0 \cos(2(\theta_0 - \theta_F))J_2(2\Delta\theta) \cos 2\omega t, \]  

(3)

where \( J_\alpha \) represents the \( \alpha \)-th order Bessel function of the first kind. The AC component of \( I \) with the frequency \( \omega \) is proportional to \( \sin(\theta_0 - \theta_F) \). To make this signal zero, which means \( \theta_0 = \theta_F \), the feedback loop is used to control the DC current flowing in the Faraday-cell (\( i_0 \)). By calibrating the relation between \( i_0 \) and \( \theta_0 \), the absolute value of \( \theta_F \) can be estimated.

III. MEASUREMENT RESULTS

To demonstrate the capability of this instrument, we have studied the magnetic behavior of a 1 BL (bilayer, 3.66x10^11 atoms/cm^2) Co film deposited on a 12 ML (monolayer, 1.39x10^11 atoms/cm^2)-thick Ag(111) film formed on Si(111)-7 x 7 substrate. The Ag film was first deposited around 100 K and annealed up to room temperature to make an atomically flat Ag(111) film[16]. Then the Co was deposited on the Ag film at room temperature. The evaporation rates of Ag and Co were separately determined by formation of RHEED patterns of surface superstructures with known amount of metals on Si(111) surface.

The RHEED pattern after the Ag film formation showed streaks indicating growth of a flat and epitaxial Ag film with (111) texture structure[16]. By depositing Co on it, additional streaks appeared outside of the Ag streaks. From the estimated lattice constant from the pattern, a fcc of hcp Co layer grew epitaxially.

Figure 4 show longitudinal hysteresis loops at RT and 20 K, and also polar hysteresis loops measured at 20 K. The hysteresis loop in the longitudinal Kerr effect becomes larger by cooling the sample; the saturation magnetization and coercive field become larger at 20 K than at RT. This is natural due to Curie-Weiss characteristic of ferromagnetic material. Only \( \sim 0.02 \) T is needed to align the spin in the direction of the magnetic field at RT and the Kerr rotation angle is \( \pm 3 \times 10^{-3} \) degree. In contrast, the magnetization on polar direction is much smaller; at RT (not shown here) there is no Kerr signal while at 20 K we can find a very small hysteresis loop in the figure. This result means that the magnetization is only in-plane in the Co film. The details of magnetic property of Co ultrathin films, especially the substrate and thickness dependences, will be published elsewhere.

Judging from the scattering of data points, we estimated the detection limit in Kerr rotation angle to be around 100 \( \mu \)deg. This resolution limit comes mainly from instability of the laser and drift in geometry of the optical path.

IV. CONCLUSIONS

In conclusion, we have developed a UHV-SMOKE system which utilizes the rotation of a pair of Sm-Co permanent magnets on both sides of the sample to apply magnetic field as large as \( \pm 0.23 \) T, and perform polar and longitudinal Kerr effect measurements. The system can be operated in the vacuum of \( \sim 10^{-11} \) Torr and at the temperature as low as 20 K. Our measurement is based on the Faraday-cell modulation technique and we have demonstrated its capability by measuring the hysteresis loops of a Co film deposited on Ag(111) film formed on Si(111) substrate. This system will be very useful in the study of surface magnetism such as ferromagnetic thin films and ferromagnetic surface superstructures.

Acknowledgments

This work has been supported by Grant-in-Aid from Japanese Society for the Promotion of Science and JSPS-NSFC-KOSEF A3 Foresight Program.

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