Observation of polarization and intensity oscillations in secondary electrons emitted from Ag/Fe(110)

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The polarization and intensity oscillations of secondary electrons emitted from Ag(111)/Fe(110) are investigated in order to study the oscillatory interlayer magnetic coupling through epitaxial Ag(111) thin films. We determined the period of the oscillation component to be 13± 1 Å, which is in close agreement with the period determined theoretically by the extremal spanning vectors of the bulk Fermi surface. [S0163-1829(98)06205-5]

Recently, ultrathin and multilayer films with new physical properties have been attracting an enormous amount of attention.[1] Especially, in the field of magnetism, the discovery of giant magnetoresistance (GMR) in Fe/Cr superlattices,[2] and the subsequent observation of oscillatory interlayer magnetic coupling through nonmagnetic materials in similar structures[3] have generated much interest, both theoretically and experimentally.[4,5] The reason for this is that it is not only fundamental, but it also has technological importance for application.

Coupling has been attributed to a Ruderman-Kittel-Kasuya-Yosida-like indirect exchange coupling mediated by conduction electrons in the interlayer,[6] or a result that comes from spin-dependent quantum confinement within the interlayer.[7] In either case, since the coupling period is determined by extremal Fermi-surface spanning vectors, the period of interlayer magnetic coupling depends on the structure and orientation of the interlayer material.

Most experimental reports on oscillatory interlayer magnetic coupling through noble-metal spacers have so far been concentrated with (100) orientation, whereas those on coupling through (111) orientation have been limited because of difficulties in observing oscillation, especially through Ag(111). To our knowledge, there have been reports from two groups[8,9] on oscillatory interlayer magnetic coupling through the Ag(111) films. According to these reports, the periods of interlayer magnetic coupling through Ag(111) films were 11 Å by GMR measurements[8] and 6 ML (14.1 Å) by Mössbauer spectroscopy.[9]

The difficulties involved in Ag(111) coupling may be due to a smaller coupling constant through (111) orientation than that through (100) orientation,[7] and to a possible ferromagnetic bias that results from the roughness of the interface between the magnetic layer and the Ag(111) layer. In the Ag(111) case, the growth mode is a Stranski-Krastanov (SK) one, which is two dimensional (2D), that is layer-by-layer, at the initial stage of film growth, and that then leads to three dimensional (3D), that is, island growth.[10,11] Therefore, when we use Ag(111) as the nonmagnetic material to make the nonmagnetic/magnetic multilayer, there may be local thinning, pinholes, or other spatial fluctuations in the Ag(111) layers. When this happens, direct exchange coupling and/or magnetic dipole coupling may play an important role in the coupling of magnetic layers through a nonmagnetic layer.[12] Then, if oscillatory interlayer magnetic coupling is weaker in the (111) orientation than in the (100), the ferromagnetic alignment of magnetic layers through the coupling via these spatial fluctuations of Ag layers may become more significant, resulting in ferromagnetic coupling oscillations.[9] If the coupling is always ferromagnetic, the oscillatory term is not observable via standard magnetometry measurements.

The spin-polarized secondary electron emission (SPSEE) method is one way of studying oscillatory interlayer magnetic coupling.[13–17] In this paper, we applied SPSEE to obtain the period of interlayer magnetic coupling in Ag(111) thin films.

The experimental setup and the procedure are almost the same as those previously reported.[13,14] In brief, the experiments were performed in a UHV system (10^{-10} Torr range). The Fe(110) substrate was cleaned by 3-keV Ar ion sputtering followed by flash heating to about 590 °C. Then, the substrate was cooled down for several minutes by thermal conduction, using a reservoir of liquid N_2, and Ag was deposited from a W filament at the rate of about 0.008 Å/s onto the Fe(110) substrate. During deposition, the sample was irradiated by a primary electron beam with energy $E_p = 2$ keV at an angle of $\theta = 50°$ from the sample surface. The temperature of the substrate was about −80 °C at the beginning of Ag deposition and about 30 °C at the end. The secondary electrons, which had energies of roughly 0–1 eV, were directed through a cylindrical mirror analyzer-type energy analyzer to a Mott detector for real-time polarization and intensity analysis.

The relative thickness of the Ag layer was monitored using a quartz crystal oscillator placed near the sample. In a separate experiment, a correction for absolute thickness was made by replacing the Fe(110) sample with another quartz crystal oscillator and directly measuring the deposited Ag thickness. Using these procedures, we determined the thickness to within ±10%.

The surface cleanness and crystallinity were checked using Auger electron spectroscopy and low-energy electron diffraction (LEED), both before and after deposition. After deposition, the LEED showed a purely hexagonal pattern. Since a few monolayers of the Ag(111) surface had a threefold (i.e., triangular) symmetry, this pattern indicated that the Ag layer grew epitaxially with a ''twin'' (111) surface plane, that is, there were two types of Ag(111) domains related to one another by 180° in-plane rotation.

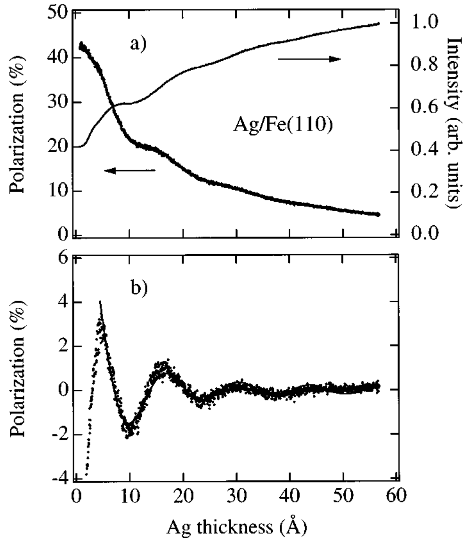

FIG. 1. (a) Secondary polarization and intensity vs Ag film thickness on Fe(110) for primary electron energies of 2 keV. The temperature of the sample was from about −80 to about 30 °C during Ag deposition. (b) Oscillation components of polarization (black dots) obtained by subtracting the smoothly changing components of Eq. (1) from the polarization data in (a). The solid line is given by the third term of Eq. (1) (see text).

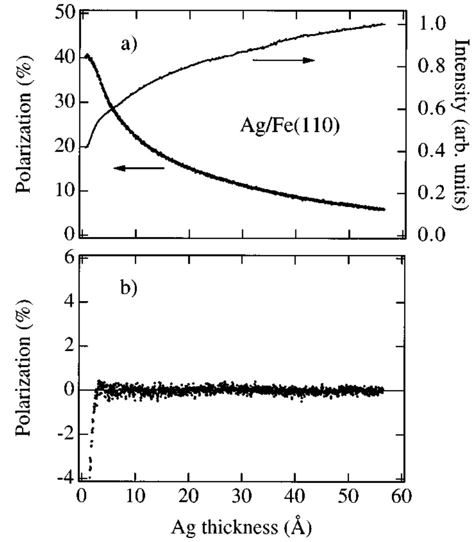

FIG. 2. (a) Secondary polarization and intensity vs Ag film thickness on Fe(110) for primary electron energies of 2 keV. The temperature of the substrate was from about 80 to about 50 °C during Ag deposition. (b) Subtraction of smoothly changing background from polarization data (a).

Figure 1(a) shows the polarization and intensity of secondary electrons emitted from Ag/Fe(110) as a function of Ag thickness t for $E_p=2$ keV. The smooth decays in background polarization are due to the relative decrease in highly polarized secondaries from the Fe substrates and the relative increase in most unpolarized secondaries from the Ag overlayer as the Ag film thickness increased. The intensity of secondary electrons also has oscillating components superimposed on smoothly changing backgrounds. The smooth changes in intensity are due to the differences in the secondary yields between Ag and Fe for $E_p=2$ keV,[16] and they might also be due to the drift in primary beam current. These oscillating components are thought to be caused by the spin-dependent quantum-well states in Ag film on an Fe substrate, and they are strongly related to oscillatory interlayer magnetic coupling.

To investigate the oscillation components of secondary polarization in detail, the background function and oscillating components were obtained by fitting the least squares of the function $P_L(t)$ to the experimental data,

$$P_L(t)=a_1\exp(-t^{a_2}/a_3)+a_4+\frac{a_5\cos[2\pi(t-a_6)/a_7]}{t^{a_8}}, \tag{1}$$

where the first and second terms correspond to the background components and the third corresponds to the oscillating components, respectively. The background function is chosen only for determining the oscillation period, so it has no physical meaning. The fitting parameters are $a_1=101.2$, $a_2=0.3652$, $a_3=1.838$, $a_4=-5.015$, $a_5=31.01$, $a_6=3.753$, $a_7=13.39$, and $a_8=1.308$. To clarify the oscillations, we subtracted the background components of Eq. (1) from the original data. The results are indicated by the black dots in Fig. 1(b). The solid line is the third term of Eq. (1). From the value of a_7 and the uncertainty of thickness measurement, we obtained a period of 13 ± 1 Å. This result is comparable to the 14.1 Å obtained by studying oscillatory interlayer magnetic coupling in Fe(110)/Ag(111) multilayers,[9] and the 14 Å theoretically obtained for Ag(111).[6,7]

In Fig. 1(b), the amplitude of polarization oscillations after the second peak rapidly reduce. This could be due not only to the damping factor of interlayer magnetic coupling strength but also to the roughness of the Ag(111) surface. Concerning the effect of roughness, experiments on the Fe/Cr/Fe(100) sandwich structure[18] and theory[6] have stated that interlayer magnetic coupling strength is reduced by surface roughness. Thus, our results on the Ag/Fe(110) bilayer system can be explained by surface roughness. In our system, Ag(111) film growth on the Fe(110) substrate was the SK mode.[10,11] Therefore, the surface of the Ag(111) films on the Fe(110) is relatively smooth until a few layers are grown, after which it progressively becomes rougher. Therefore, it is thought that damping of polarization oscillations are also due to increasing roughness caused by progressive growth.

To confirm this possibility, we conducted another experiment. With Ag/Fe(110), when the substrate temperature increases, the transfer in the growth mode from 2D to 3D may happen at an earlier stage during Ag deposition.[11] Figure 2(a) shows the polarization of secondary electrons emitted from Ag/Fe(110) as a function of t for a substrate temperature of about 80 °C at the beginning of Ag deposition and about 50 °C at the end. The primary energy was 2 keV, and the deposition rate was 0.008 Å/s. The polarization did not seem to have an oscillating component. To see if there were slight oscillations, we subtracted the background components from the original data. The background components $P_H(t)$, which have again no physical meaning, can be expressed by

$$P_H(t)=b_1\exp(-t^{b_2}/b_3)+b_4, \tag{2}$$

where the fitting parameters are $b_1 = 135.1$, $b_2 = 0.2303$, $b_3 = 1.197$, and $b_4 = -10.39$. The results of subtraction are indicated in Fig. 2(b) by the black dots. We could not observe any oscillations in secondary electron polarization. After this experiment, LEED had a diffuse hexagonal pattern, which was thought to result from the roughness of the Ag surface on the Fe(110) substrate. Therefore, we think that the polarization oscillations of secondary electrons may be hidden by surface roughness, and in the case of Ag(111)/magnetic multilayers, difficulties in observing oscillatory interlayer magnetic coupling through Ag(111) resulted from the SK growth of Ag(111) films.

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