Magnetoresistance Oscillations in Thin Inclined Magnetic Films

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Magnetoresistance (MR) oscillations were observed in thin inclined magnetic films patterned with two perpendicular stripes. The resistivities when the magnetization was parallel and perpendicular to the current could be simultaneously measured with this patterned sample. From these measurements, it was observed that the MR oscillation curves for the inclined sample shrank to a rotation angle of 90 degrees as the inclination angle increased. This could be explained by the fact that the effective field along the film surface decreased as the inclination angle increased. These results can be applicable to precision position measurements in future.

I. INTRODUCTION

The magnetoresistance (MR) effect [1–4] in single- or multi-layered magnetic thin films has been intensely studied for understanding the anisotropic, giant, and colossal MR in these systems or for the practical applications to large-size memory devices. In particular, the relative difference in resistivity when the magnetization is parallel and perpendicular to the current, or anisotropy effect, is being intensively studied in various magnetic film systems for possible applications to information storage devices or magnetic sensors. This difference in resistivity is also found to oscillate as the film sample is rotated through an axis perpendicular to the film surface. This behavior is called the MR oscillation, which is expressed as [1]

\[ \rho = \rho_\perp + (\rho_\parallel - \rho_\perp) \cos^2 \phi, \]

(1)

where \( \rho_\perp \) is the resistivity when the current is perpendicular to the magnetization, \( \rho_\parallel \) is the resistivity when the current is parallel to the magnetization, and \( \phi \) is the rotation angle.

All MR experiments presented so far were performed at an angle configuration such that the sample was in the same plane as the magnetic flux. However, recently, MR experiments with films inclined relative to the magnetic field were performed, and very interesting and unexpected results were obtained [5–10]. The rarity of papers regarding the MR behavior in inclined samples might come from the misleading fact that in this angle configuration, nothing but the demagnetization effect can be observed. However, an intrinsic difference exists between the resistivity and the magnetization measurements in the inclined samples. It is intrinsically impossible to obtain the M versus H curve properly for inclined samples. The M versus H curve is obtained by measuring the magnetization as a function of the applied field. Here, the value of the magnetization should be the magnetization along the applied field. However, in inclined samples, the out-of-plane component of the magnetization can not be saturated due to the demagnetization effect. Thus, the M versus H curve can not be obtained properly. However, even though the film surface has an angle relative to the field, the in-plane component of the magnetization (along the film surface) can be saturated. Thus, the MR behavior can be observed properly even in the inclined sample.

In this paper, we report the peculiar behavior of MR oscillations in inclined magnetic films. We measured the MR with the current parallel and perpendicular to the field simultaneously by using patterned sample films with two perpendicular stripes. We observed that the MR oscillation with the sample in the plane of magnetic flux was well explained by Eq. (1). On the other hand, the MR oscillation of the inclined sample was found to shrink to a rotation angle of 90° as the inclination angle increased. This could be explained by the fact that the effective field along the film surface decreased as the inclination angle increased.

II. EXPERIMENTAL DETAILS

The films were grown on a substrate of Corning 7059 Na-free glass with 99.999 % bulk nickel by using a thermal evaporator. The glass substrate was cleaned by boiling in distilled water for half an hour and then by using the standard wafer cleaning processes. This glass substrate was placed on the sample holder, and then the
patterned plate of stainless steel was tightly placed on it. This pattern consisted of two narrow stripes connected perpendicular to each other, as shown in Fig. 1. This was designed to measure the MR of the film perpendicular and parallel to the current simultaneously. This pattern was carefully designed and laser-cut such that the two stripes were completely identical in shape to each other.

The evaporator was pumped by a turbo-pump system down to 10^{-10} Torr and was maintained at 10^{-8} Torr throughout the evaporation process. The thickness of the film was measured with a quartz oscillator and was controlled automatically using a thickness controller via a computer. The evaporation processes mentioned above were performed in a clean room. Therefore, no contamination of the sample film was expected. During the evaporation, the growth rate was maintained at about 0.1 Å/s for the sample films.

The characteristics of the grown films were investigated utilizing X-ray diffraction (XRD), X-ray fluorescence spectrometry (XFS), and scanning electron microscopy (SEM). No impurities were detected in the XFS measurements. In the SEM image, we noted that nearly uniform grains were formed throughout the sample [8]. The film showed a principal peak in the (111) direction in XRD patterns, as shown in Fig. 2. This direction of principal peak reflected the growth direction of the film, which was identical to the easy direction of magnetization for nickel.

A schematic figure for the experimental setup is shown in Fig. 3. The film sample was placed firmly on the mounting platform of an angle controller set which was designed to control the angle of the film sample over the entire space of 4π radians. It was connected by precision rotators (rotary feedthroughs and motors, controlled by motor controllers) with an accuracy of approximately 0.2 degrees. The angle controller set, guided by three spacers to avoid any tilting, was located inside the vacuum chamber. The vacuum chamber was evacuated to reduce the effect of temperature fluctuations; however, this effect was later found to be negligible.

The MR data were obtained by using the standard four-point measurement technique. An HP 6115A precision current source was used for the current flow through the sample. The voltage drop across the sample was measured using an HP 34420 nanovoltmeter. The acquisition of data was performed through an IEEE interface card by using a computer.

III. RESULTS AND DISCUSSION

The ρ∥ and ρ⊥ were simultaneously measured by increasing the magnetic field very slowly, less than 2 Gauss
Magnetoresistance Oscillations in Thin Inclined Magnetic Films – Il-su Rhee and Kiwon Yang

Fig. 4. Resistivities $\rho_\parallel$ and $\rho_\perp$ as functions of the magnetic field. $\rho_\parallel$ and $\rho_\perp$ were simultaneously measured as shown in Fig. 1.

in a step, up to around 5000 Gauss with the sample of Fig. 1 located in the plane of the magnetic flux. The results of these measurements are shown in Fig. 4. Here, $\rho_0$ indicates the resistivity without the applied magnetic field. In this figure, the ratios of $\rho_\parallel$ and $\rho_\perp$ to $\rho_0$ are plotted as functions of the applied magnetic field. At around 100 Gauss, which is identified as the saturation magnetic field, $\rho_\parallel$ and $\rho_\perp$ sharply change as the field increases and then are slowly decrease with the field. This decrease in the resistivity components is explained by the Mott theory [11], which states that a decrease in the density at the Fermi surface of the parallel 3d-states with increasing magnetization results in a decrease in the resistivity. It can also be seen in Fig. 4 that the rate of decrease of $\rho_\perp$ above saturation is larger than the rate of decrease of the corresponding $\rho_\parallel$ [12].

The MR oscillation was observed at a fixed magnetic field of 2000 Gauss, which was well above the saturation field. This MR oscillation is shown in Fig. 5. In this figure, the theoretical curve of Eq. (1) is also plotted as a solid line. Here, it can be seen that the data fit the theoretical relation well. In Fig. 5, the data from one stripe of the film are shown, but the data for the other stripe show basically the same behavior. We also observed the MR oscillation for the inclined sample. As the inclination angle of the sample increases, the MR oscillation curve gradually deviates from the $\cos^2 \phi$ behavior and shrinks to a rotation angle of 90°.

The deformation of the MR oscillation curve is negligible in the region of lower inclination angles, but becomes

Fig. 6. MR oscillation curves for the inclined sample. These are for the $\rho_\parallel$ stripe in Fig. 1. It can be seen that the MR oscillation curves shrink to a rotation angle of 90° as the inclination angle increases.

Fig. 7. The MR oscillation curves for the inclined sample. These are for the $\rho_\perp$ stripe in Fig. 1. The MR oscillation curves can be seen to shrink to a rotation angle of 90° as the inclination angle increases.
greater in the higher angle region, particularly at inclination angles higher than 80°. The MR oscillation curves at inclination angles higher than 80 degrees are shown in Fig. 6 for \( \rho_\parallel \) in Fig. 1 and in Fig. 7 for \( \rho_\perp \) in Fig. 1. In this figure, it can be seen that the MR oscillation curves rapidly shrink to a rotation angle of 90° as the inclination angle increases toward 90°. Another characteristic of the MR oscillation curves in the higher angle region is that the ratio of the resistivity to \( \rho \) in Fig. 1 and in Fig. 7 for \( \rho_\perp \) in Fig. 6 (or \( \rho_\parallel \) in Fig. 7) at the rotation angle of 90° becomes smaller as the inclination angle increases.

It is very difficult to explain quantitatively the deformation of the MR curve with the inclination angles. However, this behavior can be explained qualitatively as follows: We note that the magnetic field along the film surface becomes smaller as the inclination angle increases. Thus, at higher inclination angles, for the \( \rho_\parallel \) stripe shown in Fig. 1, the contribution of the \( \rho_\parallel \) component to the total resistivity, \( \rho \), as the rotation angle changes, becomes larger compared with that of the \( \rho_\perp \) component. Therefore, the MR oscillation curves as shown in Fig. 6 can be observed. The same reasoning can be applied to the MR oscillation curves shown in Fig. 7. In this case, the terms \( \rho_\parallel \) and \( \rho_\perp \) in the above statements should be interchanged.

The reduction of the resistivity at a rotation angle of 90° for higher inclination angles is explained as follows: Let us first consider the difference in angle configuration between rotation angles of 0° and 90° for the inclined sample, which is shown in Fig. 8. For clarity, only the \( \rho_\parallel \) stripe in Fig. 1 is drawn on the film surface in this figure. At zero angle, that is, \( \phi = 0° \), the full strength of magnetic field is applied to the stripe; thus, only the \( \rho_\parallel \) component contributes to the total resistivity, \( \rho \). However, at \( \phi = 90° \), only the \( \rho_\perp \) component contributes to \( \rho \). Yet, in this case, the magnetic field projected on the film surface is now reduced to \( H \cos \theta \). Thus, the value of \( \rho_\perp \) depends on the inclination angle. The resistivity at this effective field of \( H \cos \theta \) can be obtained from the data shown in Fig. 4. Using these values of \( \rho_\perp \), we can plot \( \Delta \rho \) for both stripes of the film as a function of the inclination angle. This is shown in Fig. 9. In this figure, the solid lines correspond to \( \rho_0 - \rho_\perp \) and \( \rho_\parallel - \rho_0 \) obtained from the data of Fig. 4. It can be seen that the lines fit the data well.

In summary, we observed the MR oscillation of an inclined thin nickel film patterned with two stripes. For the film located in the plane of magnetic flux, the MR oscillation was well explained by the theoretical relation of Eq. (1). On the other hand, for the inclined film, the MR oscillation curves were found to shrink to a rotation angle of 90°. This behavior was explained by an effect due to a change in the magnetic component along the film surface with increasing inclination angle. These results might be applicable to precision position detection in future.

REFERENCES