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Structure and properties of MBE-grown Pt/Co multilayer, Pt/Cu doublelayer, Co/Cu doublelayer, Pt film and Cu film on Si(111)–(7 × 7) substrate

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Crystal growth mode and surface topography of a Pt/Co multilayer showing perpendicular magnetic anisotropy have been investigated by RHEED and AFM. Electric conductivity of the various films were measured and the interface effect in the electric conductivity of the multilayer is discussed.

1. Introduction

Metallic multilayer materials made by combination of a ferromagnetic metal such as Co and Fe and a noble metal such as Pt, Pd and Au exhibit superior properties as perpendicular magnetic and magneto-optic recording materials. A Pt/Co metallic multilayer is one of such hopeful materials [1–3]. In metallic multilayered films, it is considered that the interface plays an important role. However the role of the interface has not been clarified yet. Transport phenomena of electrons in various kinds of films are also necessary to be studied in connection with the interface in order to understand electronic properties.

In the present study, various kinds of films were prepared on a Si(111)–(7 × 7) substrate by molecular beam deposition, and their structure and their electronic and magnetic properties were investigated. This paper reports on the crystal growth mode and surface topography of the Pt/Co multilayer and electric conductivity of the films. The interface effect in the electric conductivity of the multilayer is discussed.

2. Experimental procedure

The preparation method of films is fundamentally the same as that described in refs. [4,5] where topography and crystallography of MBE-grown Pt films on Cu buffer layer and Si(111)–(7 × 7) substrate have been reported. Thirteen films were prepared on a 5nm thick Cu buffer layer and Si(111)–(7 × 7) substrate. They are as follows: (a) a Pt/Co multilayered film, which can be denoted as $[(Pt(3.94\ nm)/Co(1.39\ nm)]_{22}/Pt(9\ nm)$, (b) eight kinds of Pt films having various thicknesses, as will be denoted in fig. 3, (Pt/Cu doublelayer), (c) a 100 nm thick Co film, (Co/Cu doublelayer), (d) a 100 nm thick Cu film, (e) a 100 nm thick Pt film *without* Cu buffer layer and (f) an only Cu buffer layer.

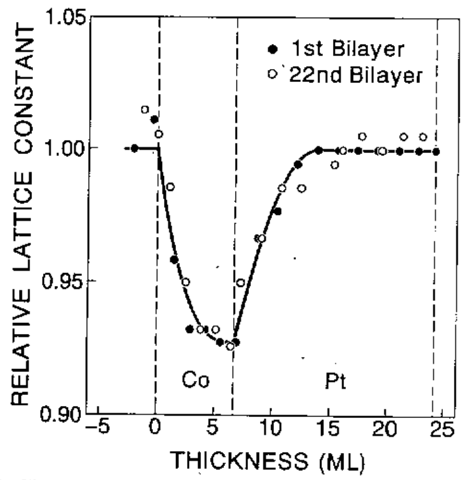

Fig. 1. Change of relative lattice constant of the Pt and the Co in the first bilayer and the 22nd bilayer as a function of thickness, showing the pseudomorphic growth of the Pt and the Co on the Cu buffer layer and Si(111)–(7×7) substrate.

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The structure of the films were in-situ observed by RHEED during the deposition and the topography of the surface was also observed by AFM in air. The magnetic properties were measured with the superconducting quantum interference device (SQUID) magnetometer and the sheet conductivity of the films were measured by the van der Pauw method.

3. Experimental results

3.1. Pseudomorphic growth

The orientational relationships between every Pt layer, every Co layer in the Pt/Co multilayer, the Cu buffer layer and the Si substrate were determined by RHEED observation and were

$$\mathrm{Co}(111)\langle 11\bar{2}\rangle \text{ or } \mathrm{Co}(0001)\langle 10\bar{1}0\rangle$$

$$\parallel \mathrm{Pt}(111)\langle 11\bar{2}\rangle$$

$$\parallel \mathrm{Cu}(111)\langle 11\bar{2}\rangle$$

$$\parallel \mathrm{Si}(111)\langle 1\bar{1}0\rangle.$$

Here, $\langle 11\bar{2}\rangle$ means both $\langle 11\bar{2}\rangle$ and $\langle \bar{1}\bar{1}2\rangle$ and we could not discriminate them.

The change of in-plane relative lattice constant was measured in in-situ RHEED observation through the deposition in forming the multilayer. Fig. 1 shows the change of relative lattice constant of the Pt and the Co in the first bilayer and the 22nd bilayer as a function of

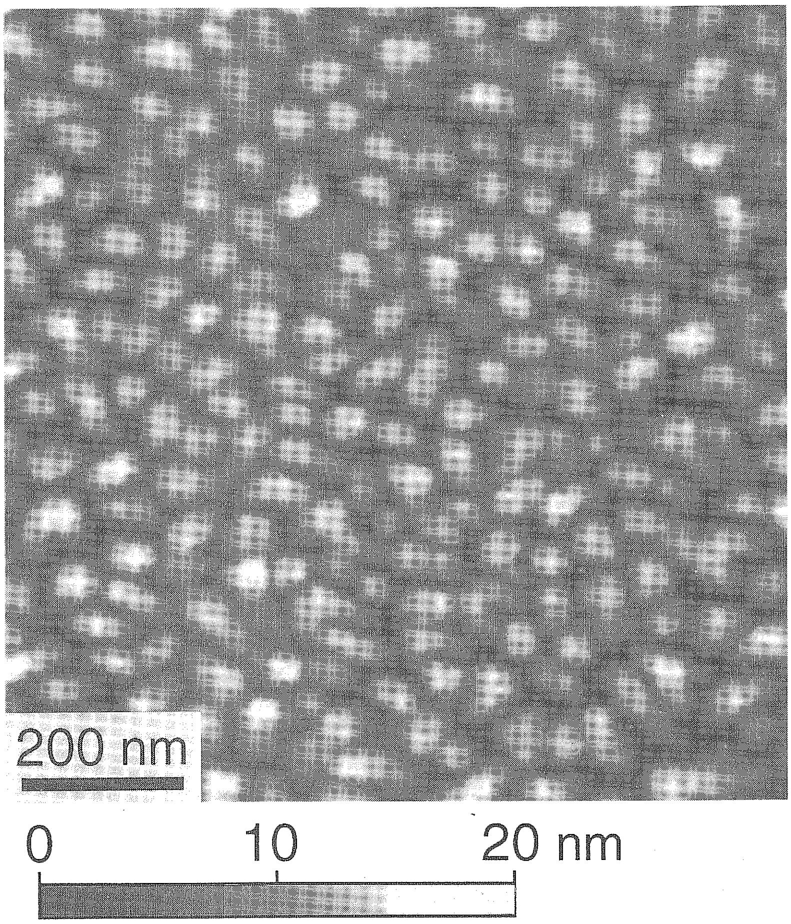

Fig. 2. An AFM image of the Pt top surface of [Pt(3.94 nm)/Co(1.39 nm)]$_{22}$ /Pt(9 nm)/Cu(5 nm)/Si(111)–(7×7).

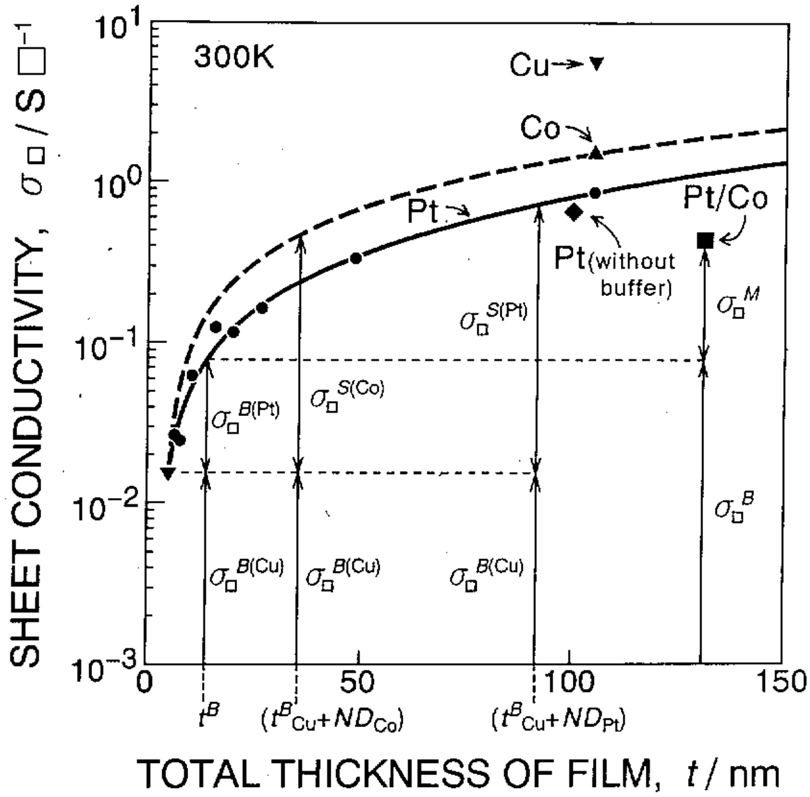

Fig. 3. Sheet conductivity of the thirteen specimens as a function of total thickness of films.

thickness. These results clearly demonstrate that through the twenty-two periods the lattice constant changes continuously and those of the Pt and Co match at the interface. Thus both the Pt and the Co grew pseudo-morphically in the alternative deposition on the Cu buffer layer.

3.2. Atomic force microscope observation

Fig. 2 is an AFM image of the Pt top surface of the Pt/Co multilayer. Principal features of the surface topography are the same as those [4,5] observed in the 100 nm thick Pt film with 5 nm thick Cu buffer layer which is the specimen (b) in the present study. Note that a thickness of 100 nm is comparable to the total thickness of the Pt in the Pt/Co multilayer. The top surface is not atomically flat, but a number of agglomerating islands exist on the surface. The difference between the top and bottom levels is about 20 nm.

3.3. Magnetic properties

The Pt/Co multilayer showed perpendicular magnetic anisotropy at both 5 and 300 K. The anisotropy energy, $K_{u,eff}$ was 5.60×10^5 J/m^3 at 300 K and 8.40×10^5 J/m^3 at 5 K. The saturation magnetization was 2.15 Wb/m^2 at 300 K and 2.25 Wb/m^2 at 5 K.

3.4. Sheet conductivity

Fig. 3 shows the sheet conductivity of the thirteen specimens at 300 K. The sheet conductivity of the Pt/Co multilayer is low in comparison with that of the Pt film (the bold line) and that of the Co film (the broken line) and is 0.44 S/□ at 300 K and 0.69 S/□ at 77 K. Since the multilayer has a number of interfaces, it is considered that the low conductivity of the Pt/Co multilayer is due to the interface effect.

4. Discussion

In order to clarify the interface effect in the transport phenomena of the multilayer we propose the analysis method which is schematically presented in fig. 4. This is equivalent to the multilayer.

The total sheet conductivity is given by

$$\sigma_\square = 1/R_\square = 1/R^M_\square + 1/R^B_\square \quad (1)$$

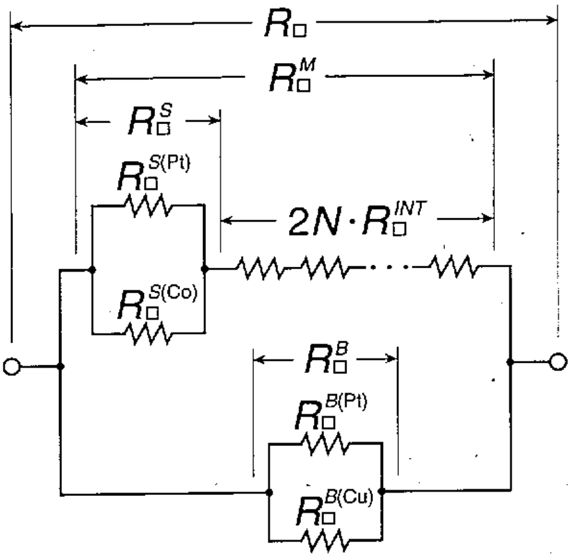

Fig. 4. Model to evaluate the interface effect in the sheet resistivity of the multilayer. $R_{\square}^{S(Pt)}$ is the the sheet resistivity of the Pt film, $R_{\square}^{S(Co)}$ is the sheet resistivity of the Co film and the other symbols are explained in the text.

where

$$R_{\square}^{M} = R_{\square}^{S} + 2N \cdot R_{\square}^{INT}, \quad (2)$$

$$1/R_{\square}^{B} = \sigma_{\square}^{B} = \sigma_{\square}^{B(Pt)} + \sigma_{\square}^{B(Cu)}, \quad (3)$$

$$1/R_{\square}^{S} = \sigma_{\square}^{S} = \sigma_{\square}^{S(Pt)} + \sigma_{\square}^{S(Co)}. \quad (4)$$

Here, $\sigma_{\square}$ is the total sheet conductivity of the film, $R_{\square}$ is the total sheet resistivity of the film, $R_{\square}^{M}$ is the sheet resistivity caused by the multilayer part, $R_{\square}^{B}$ is the sheet resistivity caused by the buffer layer part, $R_{\square}^{S}$ is the sheet resistivity of a composite film consisting of single layer films in case the film does not have the interface, N is the number of bilayers, $R_{\square}^{INT}$ is the sheet resistivity per single interface, caused by introduction of the interface where the film is multilayer, $\sigma_{\square}^{B}$ is the total sheet conductivity of all the buffer layers, $\sigma_{\square}^{B(Pt)}$ is the sheet conductivity of the Pt buffer layer, $\sigma_{\square}^{B(Cu)}$ is the sheet conductivity of the Cu buffer layer. The details of the calculation method will be described elsewhere [6].

Table 1
The sheet conductivity of the multilayer part and the buffer layer part, and their ratio

Temper-ature (T,K)	Sheet conductivity		Ratio ($\sigma_{\square}^{M}/\sigma_{\square}^{B}$)
	Multilayer ($\sigma_{\square}^{M}$, S·□$^{-1}$)	Buffer layer ($\sigma_{\square}^{B}$, S·□$^{-1}$)	
300	0.36	0.08	4.5
77	0.49	0.20	2.5

Table 2
The sheet resistivity of interface part and multilayer part, and the fraction

Temper-ature (T,K)	Sheet resistivity		Fraction $\left(\frac{2N \cdot R_{\square}^{INT}}{R_{\square}^{M}}, \%\right)$
	Interface ($2N \cdot R_{\square}^{INT}$, Ω·□$^{-1}$)	Multilayer ($R_{\square}^{M}$, Ω·□$^{-1}$)	
300	1.9	2.8	68
77	1.8	2.0	90

Assuming that the internal structures in the Pt/Co multilayer are the same as those in the Pt/Cu and Co/Cu doublelayer, we used the experimental values of $\sigma_{\square}$, $\sigma_{\square}^{B}$, $\sigma_{\square}^{S(Pt)}$, $\sigma_{\square}^{S(Co)}$ and N which are shown in fig. 3. The above assumption is reasonable because the Pt/Co multilayer and the Pt/Cu doublelayer resemble each other in orientational relationships, the grain size and the surface topography which are obtained by RHEED and STM/AFM studies. Then we obtained the sheet conductivity or the sheet resistivity of the various parts including the interface. These are presented in tables 1 and 2. The multilayer part contributes mostly in the conductivity and the buffer layer part does less. The interface part is large in the resistivity and it is comparable to that of the multilayer part at 300 K.

5. Conclusion

In the [Pt(3.94 nm)/Co(1.39 nm)]$_{22}$/Pt(9 nm)/Cu(5 nm)/Si(111)-(7 × 7) multilayer, both the Pt and the Co grew pseudomorphically in the alternative deposition and the orientational relationships were determined to be

$$Pt(111)\langle 11\bar{2}\rangle \| Cu(111)\langle 11\bar{2}\rangle \| Si(111)\langle 1\bar{1}0\rangle.$$

The AFM study revealed that a number of agglomerating islands existed on the top surface of the multilayer. The sheet conductivity of the multilayer showing perpendicular magnetic anisotropy was low in comparison with the Pt and Co films. The interface effect in the electric conductivity was evaluated and it is proved that the interface play an important role in the conductivity of the multilayer.

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