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Proceedings of Symposium on Ultrasonic Electronics, Vol. 31 (2010) pp. 21-22
6-8 December, 2010

Elastic Constant of Co/Cu Superlattice Measured by Picosecond Ultrasound

ピコ秒超音波による Co/Cu 超格子の弾性定数計測

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1. Introduction

A superlattice is a multilayer film consisting of two or more materials and thickness of each layer is atomic scale. Since superlattices have the structure that doesn't exist in the natural world, they sometimes show anomalous physical properties. For example, electric resistance of Fe/Cr and Co/Cu superlattice changes by more than 10 % when they are exposed to an external magnetic field, which is called giant magnetoresistance (GMR)[1,2] effect. The GMR effect is closely related to the antiparallel coupling of ferromagnetic layers which are separated by non-magnetic spacer layers of a defined thickness in the angstrom range, and in Co/Cu superlattice, it is reported that the value of magnetoresistance (MR) ratio oscillates as the thickness of non-magnetic Cu layer monotonically increases[3].

Magnetic and electric properties of superlattices have been widely investigated, and it has contributed to the increment of the areal density of magnetic recording devices. However, there are still ambiguities in the mechanical properties, especially in elastic constants, because of the difficulty of the measurement. For a superlattice, elastic constants reflect the composition, weak-bonding to modify the in-plane strain at the interface, the form of alloy layers and the acoustoelasticity by interfacial misfit. However, their contribution to the macroscopic elastic constants has not been completely understood.

In this research, we aim to discuss the relationship between the out-of-plane longitudinal-wave elastic constant $C_\perp$, which contributes to normal strain in the film thickness direction, and the interfacial strain of Co/Cu superlattices. $C_\perp$ is sensitive to thin inclusions aligned parallel to the film surface, and the measurement is suitable for studying structural changes at the interfaces. For determining $C_\perp$, we used picosecond ultrasound (PU) method[4,5] and x-ray reflectivity (XRR) measurement[6].

2. Specimen

A series of Co/Cu superlattice (Si/[Co(1 nm)/Cu(d_{Cu} nm)]$_{16}$) was deposited on Si(100) substrates at room temperature using RF magnetron sputtering under high vacuum conditions (3.8~9.0× 10^{-6} Pa). Argon pressure during the deposition was controlled to be 0.8 Pa. Co layer thickness was fixed to be 1 nm and Cu layer thickness was ranged from 0.5 nm to 2.5 nm. In this paper, "[Co(1 nm)/Cu(d_{Cu} nm)]$_{16}$ superlattices" is abbreviated to "Co/Cu(d_{Cu})".

3. Measurement Method of Elastic Constant

$C_\perp$ was determined using PU method. By the irradiation of the film surface with the femtosecond light pulses, acoustic phonons are generated in the thin film. Although most of them attenuate rapidly, a part of them remains to construct standing waves in the film. When the acoustic impedance of the thin film is larger than that of the substrate, the $C_\perp$ is expressed as a function of the film thickness D, mass density ρ, and resonance frequency f of the standing wave, $C_\perp = \rho v^2 = \rho(2Df)^2$. Where, v is sound velocity of longitudinal wave propagating in the film thickness direction. Resonance frequency f can be determined within the error of 2 %. In the determination of $C_\perp$, accurate measurement of the film thickness is indispensable. We determine Co and Cu layer thicknesses by XRR analysis. By the XRR analysis, we can determine the film thickness within the error of 5 %. Measurement of thin film's mass density is a difficult task, so we calculated the mass density using the density of the bulk Cu[7] and Co[8].

4. Results and Discussion

Fig. 1(a) shows the typical reflectivity change measured by PU method. Resonance frequency of the oscillation was determined by calculating the fast Fourier transform (FFT) spectrum after eliminating the background. The corresponding FFT spectrum is shown in **Fig. 1(b)**. It shows two peaks at 79.5 and 235 GHz. The former originates from

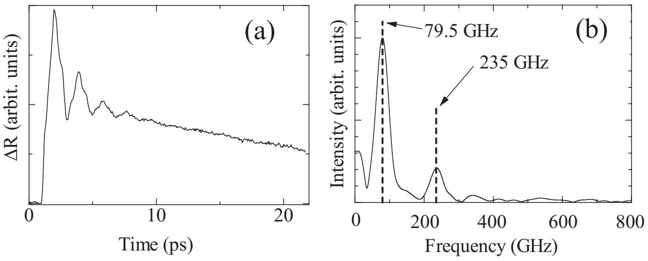

Fig. 1 (a) The as-observed reflectivity change from Co/Cu(0.94) on Si substrate. (b) The corresponding fast Fourier transform spectrum.

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the standing wave in the Co/Cu thin film and the other originates from the Brillouin-oscillation from Si substrate[9], respectively.

Fig. 2 shows the typical x-ray diffraction (XRD) spectra, in which we can find two diffraction peaks. One originates from Si substrate and the other from fundamental peak associated with the multilayer structure of Co/Cu superlattice. The fundamental peak appeared between the peak angles of the Cu(111) plane and Co(0002) plane, which indicates that the <111> direction of Cu and <0001> direction of Co aligned in the film thickness direction.

Fig. 3 shows $C_\perp$ of Co/Cu superlattices determined by experiments and $C_\perp^{\mathrm{bulk}}$ calculated from the elastic constants of the monocrystals Cu[7] and Co[8] by the simple rule of mixture, assuming that the close-packed planes of Cu and Co are parallel to the film surface, referring to the XRD spectra. $C_\perp^{\mathrm{bulk}}$ monotonically decreases as the thickness of the Cu layer increases. However, determined $C_\perp$ shows an oscillating behavior; $C_\perp$ of Co/Cu(0.75) and Co/Cu(1.90) was significantly smaller than $C_\perp^{\mathrm{bulk}}$. And, this oscillation behavior is similar to the trend in GMR reported by Parkin *et al.*[3].

Fig. 4 shows the relationship between the Cu layer thickness and the in-plane strain measured by the in-plane XRD analysis. Strain was calculated from the Cu(111) peak angles. In Fig. 4, the in-plane strain is relaxed around d_{Cu}=0.75 nm. Relaxation of the in-plane strain by the dislocation and weak-bonding regions at the interfaces is a possible reason. Then, the change in the strain would affect the macroscopic elastic constants through acoustoelasticity, but the change in the measured $C_\perp$ is so large that the acoustoelasticity cannot explain the oscillation in $C_\perp$. However, considering the softening by the dislocations and weak-bonding regions, smaller $C_\perp$ around d_{Cu}=0.75 nm is consistently explained. On the other hand, significant relaxation of the strain was not observed around d_{Cu}=1.90 nm where the second oscillation in $C_\perp$ was observed. Around this thickness, interfacial dislocations and weak-bonding regions could be introduced to release the strain in Co layers rather than Cu layers. Thus, we found the oscillation behavior of $C_\perp$ in Co/Cu superlattice, and the in-plane XRD analysis implied the relationship between the $C_\perp$ and the interfacial structure.

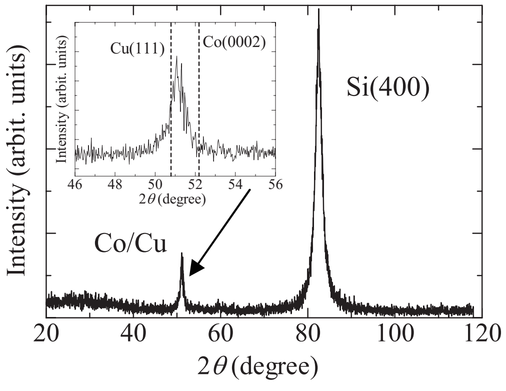

Fig. 2 XRD spectra of Co/Cu(1.74) on Si substrate.

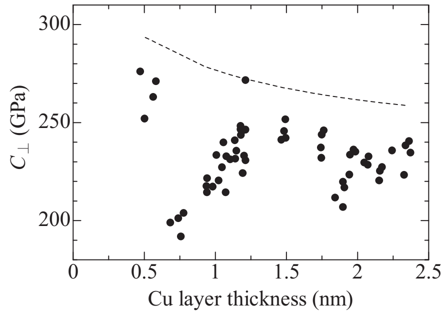

Fig. 3 Relationship between Cu layer thickness and elastic constant, $C_\perp$. Dots denote experimental results and a dashed line denotes $C_\perp^{\mathrm{bulk}}$ calculated from elastic constants of bulk Cu and Co.

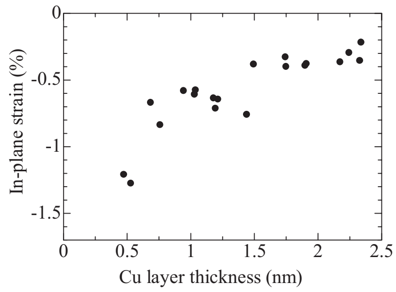

Fig. 4 Relationship between Cu layer thickness and the in-plane strain.

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