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MBE growth of ultrathin Co films on a Si(1 1 1) surface with ultrathin buffer layers

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Abstract

We have grown hetero-epitaxially ultrathin Co films on a 7×7-Si(1 1 1) surface using buffer layers of Au and Cu, where the thickness of each film is controlled to atomic-scale dimensions. The film structure and related magnetic properties are investigated. The hcp-(0 0 0 1) planes are identified in Co deposited on the Au/Cu surface, while the fcc-(1 1 1) planes are dominant with a Cu-buffer layer. Perpendicular magnetic anisotropy constants in Co indicate sharp thickness-independent interfaces and bulk-like crystallinity even in a monatomic thickness region of <2 monolayers of Co. Structure related inhomogeneities are quantified as a function of Co thickness for various overlayers by the spin-wave spectrum width. In the results, we show a successful fabrication of epitaxial growth of ultrathin Co films on the Au/Cu/Si surface with a well-defined magnetic structure. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

A hybrid ferromagnetic-semiconductor structure has been widely discussed for the potential use for spin-related electronic devices [1]. The ferromagnetic thin films with semiconductors, such as Fe/GaAs and Co/Si, have been investigated. However, the film quality of such metallic magnetic films on the semiconductor single crystal surfaces is not sufficient. The interface between those heterogeneous materials showed considerable inhomogeneities, such as, interdiffusion, alloying, and stacking faults due to the lattice mismatch. It was reported that Cu-buffer layers with the thickness of 50 nm between Co and Si(1 0 0) were used for improving the magnetic properties of Co [2]. However, the RHEED patterns of the Co films were rather spotty, indicating the rough surface and insufficient epitaxial growth. Epitaxial growth of Co/Cu/Si(1 1 1) was also presented, where both fcc-(1 1 1) and hcp-(0 0 0 1) Co were epitaxially grown on the Cu-buffer layer [3]. This epitaxial system is attractive, since the hcp-(0 0 0 1) Co shows a strong

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uniaxial perpendicular magnetic anisotropy applicable for several devices including magnetic storage media. We grow ultrathin Co films on a Si(1 1 1) surface with ultrathin buffer layers of Cu and Au. The film structure and related magnetic properties are studied for the potential use for the spin-photonics applications.

2. Film growth and structure

Details of the sample preparation are described elsewhere [4]. A HF-cleaned Si(1 1 1) wafer was annealed at 750°C in ultra-high vacuum to show a 7×7-reconstructed surface. After cooling to room temperature, a 4 nm-thick Cu-buffer layer and an additional Au-stepped wedge with various thicknesses from 0 to 5 monolayers (ML) were deposited. Then, the substrate was rotated by 90° and a Co wedge varying in thickness from 0 to 10 ML was deposited to provide a matrix of samples with different thicknesses of Au and Co under identical deposition conditions. Finally, several types of overlayer of Cu, Au, or Pd, were formed on the top of Co. All deposition rates were determined with an absolute accuracy within $\pm 10\%$ from Rutherford backscattering spectroscopy. The thickness distribution was within $\pm 2\%$ for the wedge samples.

The film structure was characterized using surface-sensitive RHEED, AES, HRTEM, and low-angle XRD (LAXRD). The magnetic properties were obtained by means of spin-wave Brillouin light scattering (BLS), polar-Kerr hysteresis curves, and a high-sensitive vibrating sample magnetometer.

In situ RHEED observations show narrow and sharp streak patterns. It indicates that the fcc-(1 1 1) planes are epitaxially grown with high crystallinity and flat surfaces, except formation of 1.4 nm-thick Cu-silicide at the Cu/Si interface. In Co/Cu(1 1 1), the fcc-(1 1 1) stacking (ABCABC—) is dominant with a small amount of hcp-(0 0 0 1), as shown in Fig. 1(a). Interestingly, those phases exist at random and a critical thickness, which indicates the structural transformation between those phases, cannot be observed. A first-principle study for the Co/Cu(1 1 1) system resulted that fcc-Co(1 1 1) was favorable on a Cu(1 1 1) surface, while Co-adatoms preferred hcp-(0 0 0 1) sites on the fcc-Co(1 1 1) [5]. Also, the lattice structure at the interface of Co/Cu is rather unclear. Moreover, we find that ultrathin Au-interlayers with the thickness down to 1 ML stabilize a single phase of hcp-Co(0 0 0 1). Fig. 1(b)

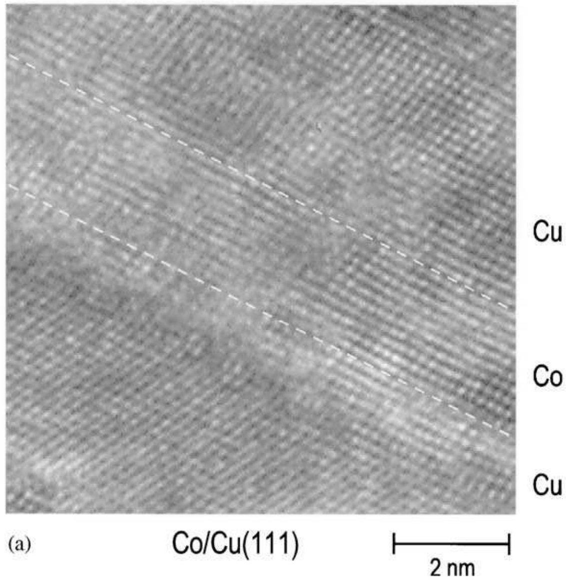

Fig. 1. Cross-sectional HRTEM images of (a) Cu/Co(10 ML)/Cu(1 1 1) and (b) Cu/Co(10 ML)/Au(3 ML)/Cu(1 1 1), respectively.

shows a lattice image of Co grown on 3 ML of Au-interlayer. A clear stacking of hcp-Co(0 0 0 1) (ABAB–) can be seen on an fcc-Au(1 1 1) stacking. The film structure with 1 ML of Au-interlayer is also shown in Fig. 2. Atomically sharp interfaces can be seen with a lateral dimension more than a few nanometers. Macroscopic interface roughness is evaluated as within 1.5 ML by LAXRD.

The lattice constant of the initial layers of Co is expanded by its hetero-epitaxial growth on Au and followed by the misfit-type strain relaxation. Details of the thickness dependence of the lattice constant of Co are given by RHHED observations [4]. An average lattice constant of the Au-interlayer on the Cu-buffer layer increases monotonically with increasing Au thickness ranging from 0 to 5 ML, and then it saturates to a bulk value of Au. The Co growth on this Au-interlayer is coherent at the interface, and the lattice constants of Co layers are expanded by the Au-interlayer. From the line width of the RHEED streak, the in-plane correlation length can be estimated as a few nanometers. The intensity of the specular diffraction from the Co-layer increases gradually with increasing Co thickness. However, we could not observe a clear oscillation of the specular beam intensity of RHEED as a function of Co thickness during the growth of Co films. Such a lack of RHEED oscillations was previously reported in Co/Cu(1 1 1), while they were observed in Co/Cu(1 0 0) prepared under identical conditions [6]. Therefore, it should be an intrinsic property of this plane.

The wedge sample of ultrathin Co films allowed us to investigate the thickness dependence of the film quality, instead of using a depth profile technique with ion irradiation and the resultant heavy interface mixing. In in situ AES analysis, the intensity ratios of Co to Au in the interlayer increase monotonically with increasing Co thickness as well as to Cu in the buffer layer. In addition, we cannot see any signal from the LMM or KLL transition of Si in our Co films. Therefore, we conclude that contamination of Au, Cu, or Si into Co magnetic layers is negligible in our films deposited without intentional substrate heating.

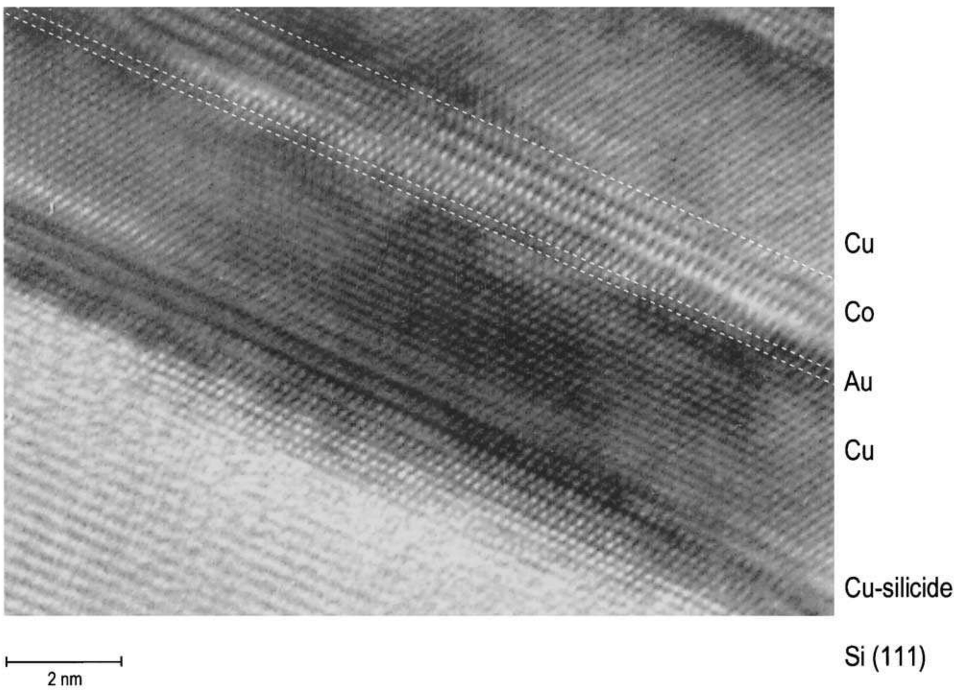

Fig. 2. A cross-sectional HRTEM image of Cu/Co(8 ML)/Au(1 ML)/Cu/Si(1 1 1).

3. Magnetic properties and discussion

More details of the Co film structure can be evaluated by magnetic properties. Interesting magnetic properties are magnetic anisotropies including an interface anisotropy, since such anisotropies are highly sensitive to the atomic scale film structure. We determine anisotropy constants from the field dependence of the spin-wave BLS frequency [4]. Fig. 3 shows the results for the first-order uniaxial perpendicular anisotropy constant $K_u^{(1)}$, where the product of $K_u^{(1)}$ t_{Co} is plotted as a function of the Co thickness t_{Co}. We observe a linear relation which indicates the existence of the interface anisotropy and it is phenomenologically expressed as $K_u^{(1)} t_{Co} = K_{u,I}^{(1)} + K_{u,V}^{(1)} t_{Co}$, where the first term is the sum of the interface anisotropy and the second term is the volume anisotropy. Therefore, this linearity shows

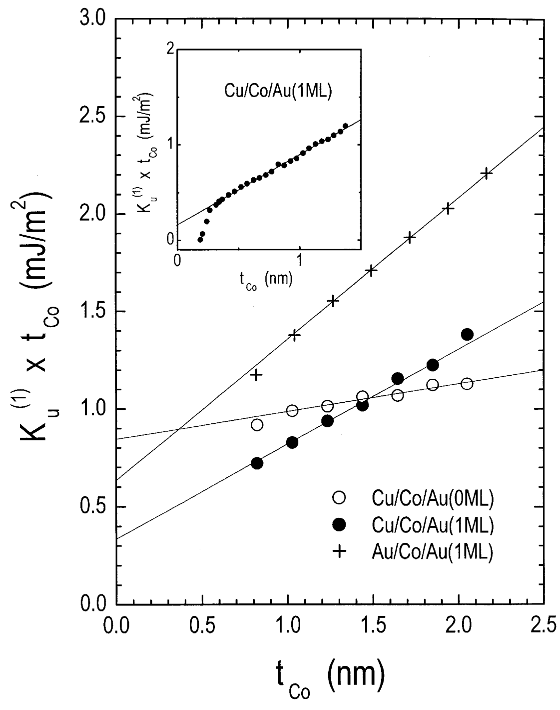

Fig. 3. Product of the first-order uniaxial perpendicular magnetic anisotropy constant $K_u^{(1)}$ determined from spin-wave measurements and the Co thickness t_{Co} as a function of t_{Co}, for various film structures. Solid lines are least square fits. Experimental errors are $<0.04\,mJ/m^2$. 1 ML of Co corresponds to 0.204 nm.

a constant value of $K_{u,I}^{(1)}$ for each Co film, assuring the thickness independent, thus, identical interface structure with an atomic scale. The value of $K_{u,V}^{(1)}$ in Cu/Co/Au(1 ML) is $-0.62\,MJ/m^3$, which is comparable with the value of $-0.56\,MJ/m^3$ determined in well-characterized hcp-Co [7]. The smaller value of $K_{u,V}^{(1)}$ in Cu/Co/Cu is due to the fcc phase and slight contamination of other planes like (1 0 0) and (1 1 0). We demonstrate that the $K_{u,V}^{(1)}$ in Cu/Co/Cu is transformed into the bulk value of Co with inserting only one ML of Au-interlayer. Moreover, as can be seen, both the constant $K_{u,I}^{(1)}$ and $K_{u,V}^{(1)}$ are maintained in the monatomic thickness region of Co like down to 1.4 ML (inset). This critical thickness of 1.4 ML coincides well with the interface roughness of 1.5 ML, which is quantified by LAXRD. Therefore, we conclude that the atomically sharp interfaces and the bulk-like crystallinity are successfully obtained in such ultrathin Co films, which was grown hetero-epitaxially on a Si(1 1 1) surface with 1 ML of Au-interlayer on the Cu-buffer layer. In addition, we show effects of overlayer on the magnetic anisotropies. With the Au-overlayer instead of Cu, both constants $K_{u,I}^{(1)}$ and $K_{u,V}^{(1)}$ increase significantly. These effects are attributed to additional strain caused by the Au-overlayer, since the lattice constant of Au is 14%—higher than that of Co. The local strain and resultant dislocation formation near the upper interface between Co and Au can cause such increase in the interface anisotropy. In addition, uniform strain can enhance the volume anisotropy.

Finally, we find the magnetic-field-dependent line broadening of the spin-wave BLS spectrum, which enables us to determine quantitatively magnetic inhomogeneities. From fitted calculations, the field-independent width (Δf_0) of the spin-wave spectrum decreases abruptly with the insertion of 1 ML-thick Au-interlayer [8]. This result agrees well with our direct observations for the lattice structure described above. The normalized distribution of $K_u^{(1)}$ shows a minimum as low as 1.5% for 1 ML of Au. The detailed Co-thickness dependence of Δf_0 in ultrathin region of Co with various overlayer materials is shown in Fig. 4. This Δf_0 means the field independent, thus, structure-related inhomogeneities, such as, dislocations,

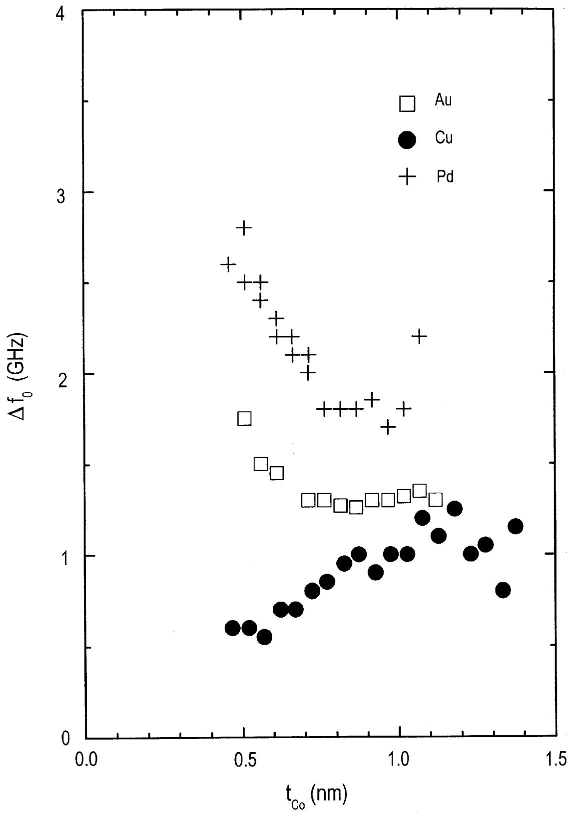

Fig. 4. Parameters indicating structure-related inhomogeneities Δf_0 as a function of t_{Co}, for Cu-, Au-, or Pd-overlayer.

stacking faults, and defects. With the Au- or Pd-overlayer, such inhomogeneities become significant below 3 ML of Co. It indicates that those overlayers cause significant structure-related inhomogeneities near the upper interface of Co, with the thickness range of 3 ML.

In summary, we have successfully grown ultrathin Co films on Si(1 1 1) surfaces with the combination of ultrathin Au-interlayers and Cu-buffer layers. A hcp-(0 0 0 1) plane is identified in Co deposited on the Au-interlayer. Perpendicular magnetic anisotropy constants in Co indicate the thickness-independent sharp interfaces and the bulk-like crystallinity even in the monatomic film region less than 2 ML.

Acknowledgements

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