Evolution of Stress With Film Thickness in Co Films on InP(001)

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We investigated the stress evolution of a Co/InP(001) by a highly sensitive optical deflection-detecting system in an ultra high vacuum (UHV) chamber. Stress results are analyzed and discussed by correlating to the growth morphology obtained from scanning tunneling microscopy (STM) measurements and to the structure of the Co/InP obtained from high resolution transmission electron microscopy (HRTEM) measurements. Abrupt compressive stress, which is seen at the initial stage of the Co growth, might be due to the effect of the adsorption of Co on the InP. Subsequent tensile stress is closely related to the formation of continuous film by the coalescence of Co islands on the InP as shown in STM images. In addition, it is observed from HRTEM images that the lattice relaxation along the c-axis of hcp Co has an effect on tensile stress.

Index Terms—Compressive stress, high resolution transmission electron microscopy (HRTEM), scanning tunneling microscopy (STM), tensile stress.

I. INTRODUCTION

FERROMAGNETIC metal/semiconductor (FM/SC) hybrid systems have been investigated intensively as potential systems due to the possibility of application to spintronic devices [1]–[3]. For the application of FM/SC, it is very important to study the properties of the interface between a ferromagnetic metal and a semiconductor, because these properties play critical roles in characteristics of spintronic devices. For example, structural, electrical, and magnetic properties of a FM/SC system are influenced by the interfacial properties such as interdiffusion, and lattice mismatch-induced strain. Among such interfacial properties, stress, which is inevitably produced in heterostructure, has a huge effect on the structural stability and the reliable operation of devices. Therefore, to understand the stress evolution of a FM/SC system is essential for both fundamental interest and technological applications.

So far, among FM/SC systems, a Fe/GaAs and a Co/GaAs have been considered as the prototypical FM/SC systems. However, among other FM/SC systems, a Co/InP system is also an interesting FM/SC system; Co, which has the high spin polarization of the carriers at the Fermi level, is of great interest for applications in information storage media, and giant magnetoresistance (GMR) devices [4]. InP, as a promising III-V semiconductor, is used in high speed opto-electronic devices due to a direct bandgap energy and a high carrier mobility [5]. In addition, the Co/InP system is a very interesting system from the view point of stress evolution because it shows complex lattice mismatch. When Co is hcp structure, Co(1120)[001][InP(001)]110 yield lattice mismatch of 1.97% along the c axis of Co and ~4.4% in the orthogonal direction, where it is expected to induce a tensile stress and a compressive stress, respectively.

In the present work, we have investigated the stress evolution of a Co/InP(001) via a highly sensitive optical deflection-detecting system in an ultra high vacuum (UHV) chamber. Stress results are correlated to the growth morphology of Co films on an InP substrate by scanning tunneling microscopy (STM) and are also explained by the structures in the interface from high resolution transmission electron microscopy (HRTEM) results.

II. EXPERIMENTS

In situ stress measurement of Co films on an InP (001) was performed in a UHV chamber which has a base pressure less than $2 \times 10^{-10}$ Torr. InP substrates of 25 $\mu$m (l) $\times$ 15 mm (w) were used in stress measurement. After ultrasonic cleaning in ethanol, the InP substrate was clamped to a cantilever on a molybdenum plate and was put into the UHV chamber. To obtain a clean surface, the InP substrate was treated with the several cycles of Ar$^+$ ion bombardment and annealing (IBA). During the IBA processes, the InP substrate was sputtered by Ar$^+$ ions at the energy of 300 eV, and then was annealed at 400°C. Co films were deposited on the InP at ambient temperature from a water-cooled e-beam evaporator at a rate of 0.76 A/min. In situ stress of the Co/InP system was performed by using a highly sensitive laser deflection system with a one dimensional position sensitive detector (PSD) which has a position resolution of 0.3 $\mu$m [6], [7]. The occurring stress in the film was calculated by Stoney’s equation [8]. In this experiment, Co...
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Fig. 1. Film force ($\sigma \cdot t_f$) as a function of Co film thickness ($t_f$) at room temperature.

where, $E_s$, $\nu_s$, $t_s$, $t_f$ and R correspond to Young’s modulus, Poisson’s ratio, the thickness of the substrate, the film thickness, and the curvature of substrate, respectively ($E_s = 1.01 \times 10^{11}$ N/m$^2$, and $\nu_s = 0.357$). In this experiment, “stress” means the calculated average stress which is delivered to the InP substrate during Co deposition. Measurement error was $\pm 0.0048$ N/m, which was calculated from Inset of Fig. 1. (Inset shows film force as a function of film thickness before deposition.) During the evaporation the pressure was maintained at a value less than $5 \times 10^{-10}$ Torr. To elucidate the relation of growth morphology to the stress evolution, scanning tunneling microscopy (STM) measurements of Co/InP were performed at specific Co thicknesses. In addition, to correlate the stress evolution of Co/InP to the structure of Co film in the interface, HRTEM measurements were carried out on the Co films of 50 nm on the InP substrate.

III. RESULTS AND DISCUSSION

In Fig. 1, we demonstrate a film force curve as a function of the Co film thickness during the fabrication of the Co/InP(001) sample. Here, the positive and negative slopes imply the existence of tensile and compressive stresses, respectively. As shown in Fig. 1, the stress evolution of Co/InP could be characterized by the following features: (i) large compressive stress up to $\sim 9.0$ GPa at the initial stage of the Co growth less than the Co thickness of 2 Å. (ii) abrupt transition to large tensile stress larger than 2 Å and subsequent tensile stress relaxation. The large compressive stress at the beginning of the Co growth might be attributed to the intrinsic surface stress effect by Co adsorption on the InP, as reported to several investigations [10]–[13]. At the initial stage of growth, the adsorption of Co atoms on the InP leads to the formation of new interface, which consists of Co, In, and P atoms and such a new interface induces compressive stress. This compressive stress is maintained up to Co film thickness of 2 Å. Following the initial large compressive stress, a tensile stress is developed at the Co thickness larger than 2 Å. A physical origin for the development of tensile stress observed in this stage can be understood by the following two effects: (i) the formation of continuous film by coalescence and (ii) a lattice mismatch between Co and InP.

In order to correlate the stress evolution to the growth morphology of Co on InP surface, STM measurements were taken. Fig. 2(a) shows an STM image of the Co film with the nominal thickness of 0.2 Å on the InP(2 × 4) reconstructed surface. It can be found that small Co clusters of typically 0.5 Å in height and 1.4 nm in diameter are formed on the InP surface. Interestingly, it is observed that the Co clusters are preferentially adsorbed on the rows of the InP surface along the $[1\ 1\ 0]$ direction of the InP instead of falling into the trench of the InP(2 × 4) reconstructed surfaces. According to the previous works it is well known that an InP surface becomes In-rich (2 × 4) reconstructed surface by ion bombardment and annealing (IBA) [14], [15]. In such an In-rich surface, the rows of the InP(2 × 4) surface are energetically favored when In-P dimer or P-P dimer is formed [16]. In addition, it is known from several investigations that P atoms move to the interface of the Co/InP and interact with Co atoms and the interdiffusion maintains up to the Co film thickness of 7 Å [17]–[19]. Therefore, the preferential adsorption of Co islands on the row of the InP might be due to the interaction between Co atoms and P atoms. Compressive stress at the initial stage of growth, which is seen in Fig. 1, is enlightened by an adsorption of Co atoms and Co-P bonding. According to STM study on Fe/GaAs, the nucleation of Fe on GaAs breaks As dimer bonds and Fe-As-Fe chains are formed [20]. Similarly, it is expected that Co-P bonds form at the initial stage of the Co growth and have an effect on the compressive stress. Fig. 2(b) shows an STM image of the Co/InP system at the Co thickness of 2 Å. As shown in Fig. 2(b), small Co clusters are combined to form

Fig. 2. 50 nm × 50 nm STM images of Co/InP(2 × 4) surface at several Co thicknesses : (a) 0.2 Å (b) 2 Å (c) 4 Å and (d) 12 Å.
larger islands which are normally 0.1 nm to 0.4 nm in height and 3 nm to 5 nm in diameter. Additionally, Co islands start to wet the InP surface at this Co thickness. The wetting process is closely related to the tendency that the relaxation of surface stress finished at Co coverage of 2 Å in Fig. 1. Fig. 2(c) shows that Co films completely wet InP surface at the Co film thickness of 4 Å. RMS roughness in Fig. 2(c) is 0.68 Å, which is smaller than the value of 0.82 Å in Fig. 2(b). This means that small Co islands coalesce and form a completely continuous film at the Co thickness of 4 Å. Fig. 2(d) represents an STM image of the Co/InP with the Co coverage of 12 Å. In Fig. 2(d), small-sized islands seen in Fig. 2(b) are not observed, but lumps of Co are only visible. Such lumps of Co indicate that second nucleation of the Co film occurs after continuous films are formed. RMS roughness in Fig. 2(d) is 0.95 Å, which is due to such lumps of Co. Tensile stress relaxation shown in Fig. 1 might be closely related to such a growth mode.

In order to verify the lattice mismatch-induced tensile stress in the Co/InP system, we have performed HRTEM measurements. Fig. 3 shows a selected area diffraction (SAD) pattern and HRTEM images with the zone axis along the [110] direction of the InP. As shown in Fig. 3(a), the SAD pattern shows Co ring patterns which imply that the Co films on the InP form polycrystalline structure. As described in indices of Fig. 3(a), the (0002) spot of hcp Co is positioned with the (0002) spot of the InP. This means that crystallites exist with the c-axis of Co arranged along the [110] direction of the InP. In addition, the (1100) spots of hcp Co are also shown, which implies the existence of crystallites with the c-axis of Co along the InP[110]. Such a polycrystalline structure of hcp Co is also observed in HRTEM images. In Fig. 3(b), three different structures are observed in rectangles. In the magnified image of Fig. 3(c), it shows the fringe distance of 3.02 Å. It might be related to the (111) plane of hcp Co, when it is inferred from the SAD pattern shown in Fig. 3(a). This value is larger than twice the plane distance of hcp Co(111)(d_111: 1.48 Å). The increased value might be attributed to the elongation of Co lattice in the interface. In the magnified image of Fig. 3(d), other structure is observed. In this figure, the fringe distance corresponds to 4.88 Å. It might be related to the (1110) plane of hcp Co, as inferred from SAD patterns. Note that the fringe distance of 4.88 Å is 2.7% smaller value than 4(d_111: 1.25 Å). Such a decreased value might be due to the contraction along plane perpendicular direction by correlating to the extension along the c-axis of hcp Co. In magnified HRTEM image of Fig. 3(e), the fringe distance is 2.15 Å. Interestingly enough, this is nearly consistent with the plane distance of hcp Co(1110)(d_1110: 2.16 Å), which implies that the lattice of Co is not elongated along this direction. Compressive stress is expected from the lattice mismatch along the direction of Co(1110)[0001][InP[001][110]. However, the contraction of lattice along this direction is not seen, which indicate that lattice mismatch-induced stress is not produced along this direction. The increased fringe distance in the aforementioned (11102) spot in Fig. 3(c) might be due to the increase of the (0002) plane distance. Consequently, lattice mismatch-induced tensile stress is attributed to the lattice relaxation along the c-axis of Co.

Fig. 3. (a) SAD pattern and (b) HRTEM image of Co/InP. Three magnified images of (c), (d) and (e) correspond to three rectangular areas shown in (b). When SAD pattern and plane distances in each fringe are considered, (c), (d), and (e) correspond to the planes of Co(1102), Co(1120) and Co(1100), respectively.

According to our previous work [21], the Co/InP shows both in plane and perpendicular magnetic anisotropies at the regime.
of Co thickness from 8 ML to 16 ML. It suggests that there exist crystallites whose c-axes of hcp Co are tilted from the (001) plane of the InP. Note that in Fig. 3(d), the (1120) plane of hcp Co is not completely consistent with the (001) plane of InP but is tilted. Similarly, it is expected that there exist crystallites of hcp Co whose c-axes are tilted from the (001) plane of the InP. Therefore, it might contribute to the perpendicular magnetic anisotropy at the initial stage of Co deposition.

IV. CONCLUSION

In conclusion, we investigated a stress evolution of a Co/InP system with in situ stress measurement. Large compressive stress at the beginning of deposition might be attributed to the adsorption of Co as shown in STM images. Following tensile stress is closely related to the formation of continuous Co film after the coalescence of Co islands. HRTEM results reveal that the elongation of the c-axis of Co is dominant and it contributes to the tensile stress.

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