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Comparative Study of Magnetization of Co Thin Films Deposited on Glass, GaAs (001) and Si (001) Substrates

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Abstract: The effect of surface induced anisotropy and interfacial anisotropy on the magnetic properties of Co thin films have been presented. The surface roughness of 100 nm Co film on both the glass and Si (001) substrate is found to be ~ 50 Oe. But the surface roughness of the same thick Co film on GaAs (001) substrate is enhanced to ~ 80 Oe. The enhancement of coercivity of Co thin film on GaAs (001) substrate is due to the special interaction between transition metal Co and GaAs (001). The anisotropy field due to the cobalt silicide interface is responsible for large saturation field required to saturate the Co/Si sample. The squareness of Co thin film on both the glass and GaAs (001) is ~ 1. On the other hand, it is reduced to 0.45 for Co/Si system. Both the surface induced and interfacial anisotropy fields influence the shape of the hysteresis loop.

Keywords: Thin film, Magnetization, Surface roughness, Interface, Squareness, Anisotropy.

1 Introduction

The integration of ferromagnetic and semiconductor materials in spin electronics has recently become a promising key for device physics [1-2]. It is known that surface and interface of ferromagnetic thin film influence the magnetic properties, such as magnetic hysteresis, magnetic anisotropy, coercive force, magnetoresistance as well as structure of the magnetic domain [3-7]. The structural and magnetic properties depend strongly on the film preparation conditions, quality of the substrate, substrate cleaning method and types of substrate. Therefore, it is important to perform magnetic and morphological investigations of the identical samples deposited in the same preparation conditions. In this research, identical thin films of Co are deposited on glass, GaAs (001) and Si (001) substrates. Ferromagnetic/semiconductor hybrid structures of Co/GaAs and Co/Si are of particular interest in the field of spintronics because of sensitive dependence of magnetic properties on structural parameters near the interface due to the lattice mismatch between the ferromagnetic Co and semiconductor substrates [8-10]. Specially, Co films have been widely investigated due to their larger magnetic anisotropy constant [11-12]. The hexagonal-close packed (hcp) structure is the most stable phase for bulk Co at room temperature. Epitaxial growth can be used to obtain face-centered-cubic (fcc) phase at room temperature. Unfortunately, cobalt reacts with Si to form cobalt silicide alloys very easily and also creates a disordered Co/Si interface [13]. It is very difficult to grow Co film epitaxially and generally characterized on hcp or polycrystalline phase with in-plane uniaxial magnetic anisotropy [14]. Sometimes Au and Cu buffer layers are used to prevent inter diffusion of Co and Si [15-16]. If the thickness of the buffer layer is tens or even hundreds of nanometer then the spin injection through the metal/semiconductor is reduced significantly [16-18].

Magnetic and morphological properties of Co thin film on plasma etched Si (100) substrate were investigated by Li and Wang [11]. They found that the uniaxial anisotropy decreased with the increase of surface roughness and disappeared for the roughest film. Their investigated result also suggested that, with the increasing surface roughness, the magnetization reversal changed gradually from magnetization rotation dominated for the smoothest films to domain-wall motion dominated for the roughest films. Sakamaki and Amemiya have investigated the effect of surface roughness and interface on the magnetic properties of Co thin film [19]. They have observed that the rough sample with rough interface favors in-plane magnetization more than the sample with sharp interface.

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2 Experimental details

Substrates are etched by using semiconductor grade chemical compound (Semico 23 clean, Japan). The substrates are immersed in the solution of Semico 23 clean and the glass container containing the solution is placed on an ultrasonic bath for 5 minutes. The substrates are rinsed with deionized water. The substrates are dried by flowing Nitrogen gas. Si–doped GaAs (001) substrate (GIRMET Ltd., Russia) with an electron carrier concentration of 1×10^{24} m^{-3} was used in this research. The deposition rate of Co film was 10 $Ås^{-1}$ onto glass, GaAs (001) and Si (001) substrates by e-beam evaporation method at a base pressure of 5×10^{-6} Torr. The substrate was kept at room temperature during the film deposition.

The film thickness was measured by Fizeau interferometer fringe method using Sodium lamp. Magnetization was measured using VSM at room temperature. The magnetic field was parallel to the film plane. The roughness of the Co films deposited onto glass, GaAs, Si substrates was measured by an Atomic Force Microscopy (XE-100 SPM, Perk system) located in our university central science laboratory. All AFM measurements are done in non-contact mode of SPM. In X-ray diffraction measurement, the Co films grown on GaAs (001) and Si substrates exhibited polycrystalline *hcp* structure. The measurements were performed using an X-Ray diffractometer with Cu Kα1 radiation. The characterizations were carried out in ambient air at room temperature.

3 Results and Discussion

Many magnetic properties such as magnetic anisotropy, magnetization reversal process, Coercivity and magnetoresistance are affected by surface and interface of ferromagnetic thin film. In addition to the surface and interface of ferromagnetic film on semiconductor substrate, it is known that the thickness, the composition, preparation conditions and crystalline structure also determine the magnetic properties of the films. Therefore, to understand the effect of surface roughness and interface on magnetic properties, other factors which influence the magnetic properties must be controlled. In this study, 100 nm Co thin films are deposited on glass, GaAs (001) and Si (001) substrates at room temperature. The magnetization of as-deposited Co film is carried out in ambient air at room temperature.

The magnetization processes of 100 nm Co film are shown in figure-1. It is seen from the figure that the coercivity of 100 nm Co film on glass substrate is only 50 Oe and the squareness of the hysteresis loop is about 1. On the other hand, the coercivity of the same thick Co film on GaAs (001) is 80 Oe and the squareness is ~0.9. The coercivity of 100 nm Co on Si (001) substrate is 50 Oe but the same sample shows a remarkable reduction of the squareness. The squareness of Co/Si is only 0.45. The saturation field of 100 nm Co on glass substrate is ~ 60 Oe where as it is 200 Oe for the same thick Co on GaAs (001). The value of saturation field of 100 nm Co on Si (001) substrate is increased to 250 Oe. It is known that the shape of the hysteresis loop depends on the anisotropy energy as well as roughness of the film. The relationship between coercivity and roughness for a relatively thick film is complicated, rather than a simple monotonic relationship [20]. In general, films cannot be grown perfectly. Roughness appearing in the film plays significant role in modulating the magnetic properties. For in-plane magnetization, local magnetizing fields at the surface and interface reduce its anisotropy. The coercivity of ferromagnetic field increases with the increase of surface roughness [4].

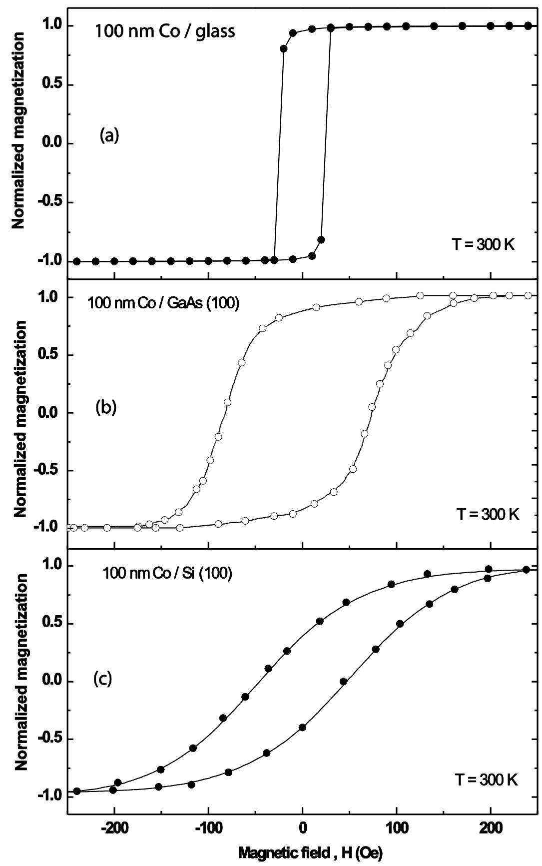

Figure 1: Magnetization process of 100 nm Co thin films on (a) glass, (b) GaAs and (c) Si substrates. The magnetic field was parallel to the film plane. Measurement is carried out at room temperature.

In order to understand the effect of surface roughness on coercivity, the roughness was studied by an AFM. Figure-2 shows the 3D AFM images of 100 nm Co films on glass and Si (001) substrate. The corresponding 2D AFM images of the same thick films on glass and Si (001) are shown in figure-3. Figure-4 shows the 2D AFM image of 100 nm Co film on GaAs (001) substrate. The rms value of the surface roughness of 100 nm Co on glass substrate is ~10 nm. Our previous study on Co/GaAs (001) system showed that the rms value of the surface roughness of 100 nm Co film is only ~ 2 nm [4]. On the other hand, the rms value of the surface roughness of 100 nm Co film on Si (001) substrate is found to be 18 nm. It is seen from figure-3 that the grain size of Co/glass is very small. It becomes larger in Co thin film on Si (001) substrate. The value of grain size of Co thin film is increased significantly when deposited on GaAs (001) substrate. It is speculated that the enhanced coercivity is due to a special interaction between Co film and GaAs (001) substrate, since enhancement of coercivity did not appear in Co film deposited on Si (0 0 1) and glass substrate [4].

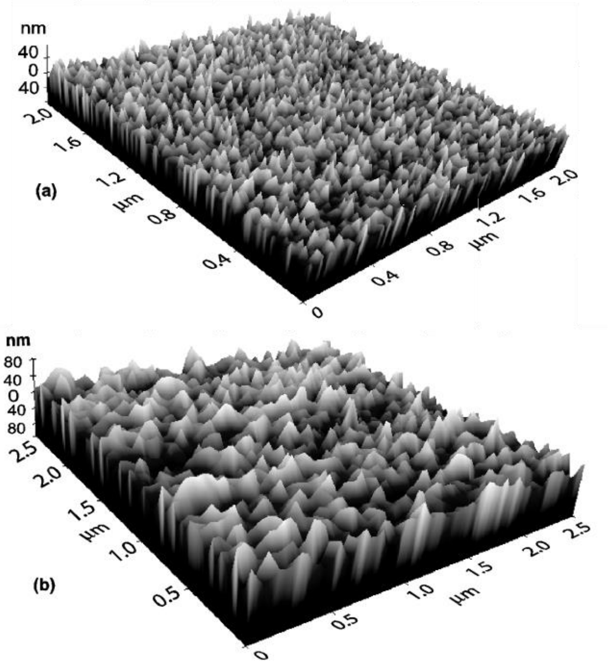

Figure 2: 3D AFM image of 100 nm Co film on glass substrate (a) and Si (001) substrate (b).

The large saturation field and the reduction of the squareness of Co films as shown in figure-1 can be well understood by the magnetization process explanation sketch as shown in figure-5. There is no intermixing between Co and glass substrate and the interface is sharp. Therefore, the anisotropy field from the interface is zero. Only surface induced anisotropy field (B_{surf_ani}) and in-plane anisotropy field (B_{ani}) are present. The grain size of Co thin film on glass is very small. Therefore, the anisotropy field due to the rough surface is small for Co film glass substrate. Only the in-plane anisotropy field dominates hysteresis loop. When the magnetic field is applied parallel to the film plane, magnetic saturation takes place rapidly as shown in figure-1a. Therefore, the magnetization process of 100 nm Co on glass showed almost square like hysteresis loop. But Co diffuse into Si substrate and interface is present between Co film and Si substrate. For Co/Si system, surface induced anisotropy field (B_{surf_ani}), in-plane anisotropy field (B_{ani}) and interfacial anisotropy field (B_{int_ani}) due to the interface are present (figure-5b). It is known that the interfacial anisotropy field and surface induced anisotropy fields are laid perpendicular to the film plane [21-22].

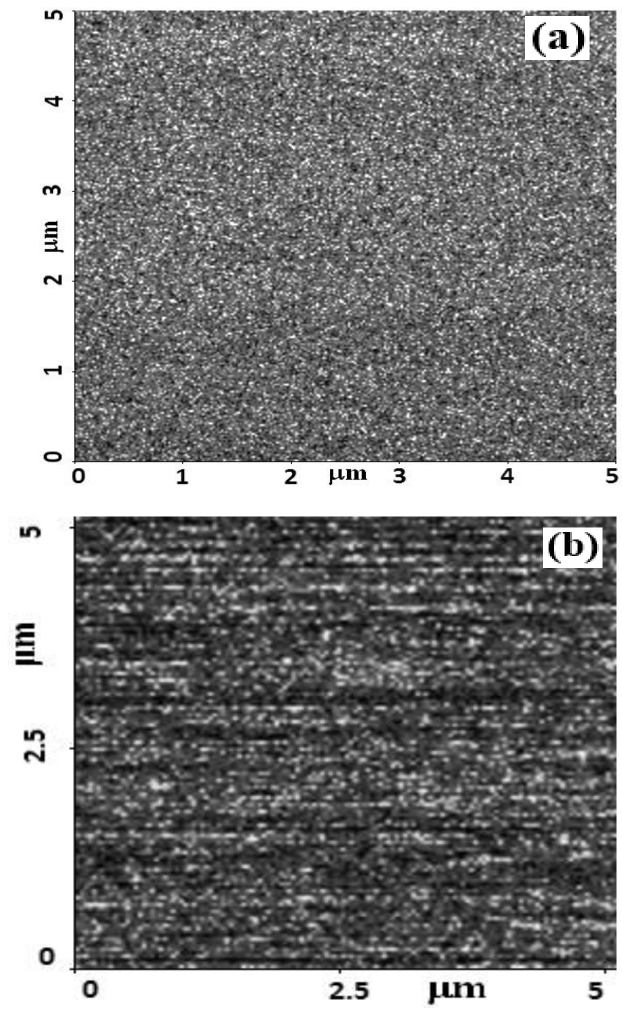

Figure 3: 2D AFM images of 100 nm Co thin film on glass (a) and Si (001) (b) substrate.

When the magnetic field is applied parallel to the film plane, the saturation takes place slowly as shown in figure-1c and in figure-5b. This is due to the fact that, the in-plane anisotropy field is laid parallel to the film plane but the interfacial anisotropy field and surface induced anisotropy fields are laid perpendicular to the film plane. Therefore, a large value of external magnetic field is required for saturating the sample. Due to this large external saturating magnetic field, the squareness of the hysteresis loop is reduced.

On the On the other hand, the shape of the hysteresis loop of 100 nm Co on GaAs (001) (figure-1b) is different than that of 100 nm Co film on glass and Si (001) substrate. It is known that cobalt begins to react with GaAs (001) at relatively higher temperature (> 370 degree) [23]. Cobalt did not react with GaAs (001) in our sample. Therefore, the interfacial anisotropy is zero. For Co/GaAs system, surface induced anisotropy field (B_{surf_ani}) and in-plane anisotropy field (B_{ani}) are present. It is evident from our previous report that the surface roughness is very small for Co film on GaAs (001).

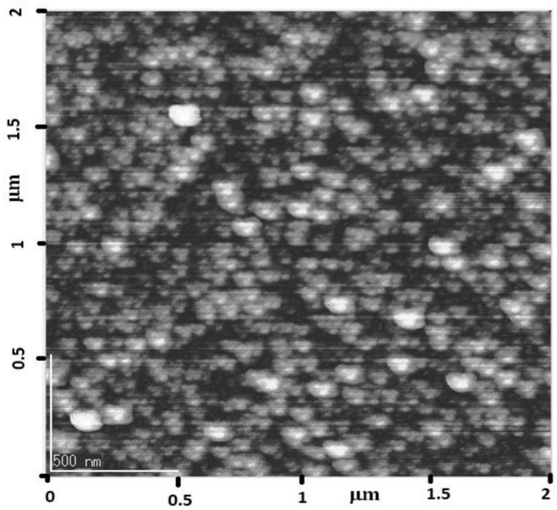

Figure 4: 2D AFM image of 100 nm Co film on GaAs (001) substrate.

The surface induced anisotropy field is small and laid perpendicular to the film plane. The in-plane anisotropy is much larger than the surface induced anisotropy field. When the magnetic field is applied parallel to the film plane, the saturation takes place rapidly as shown in figure-1b.

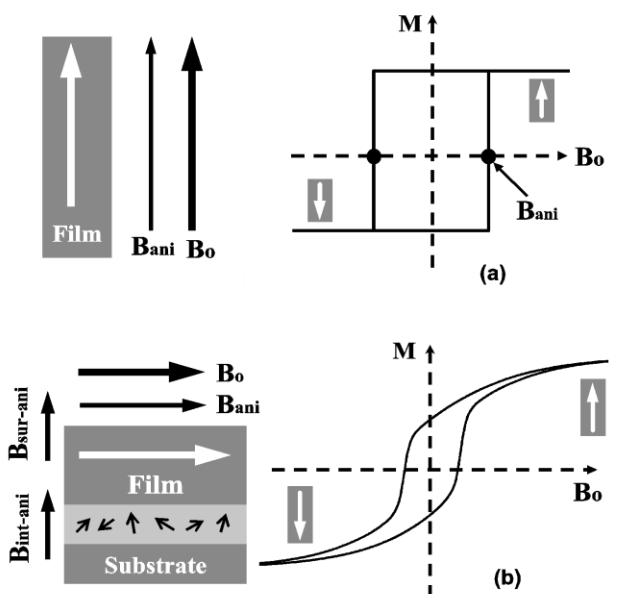

Figure 5: Magnetization process thin films without the influence of anisotropy field (a) and under the influence of anisotropy fields due to the surface roughness and interface (b). The magnetic field $\mathbf{B_o}$ is parallel to the film plane.

This is due to the fact that, the in-plane anisotropy field is laid parallel to the film plane but the surface induced anisotropy fields is laid perpendicular to the film plane. Therefore, a relatively small value of external magnetic field is required for saturating the sample. The squareness of the hysteresis loop is increased due to the relatively small external saturating magnetic field.

4 Conclusions

Magnetic anisotropy due to surface roughness and interface influences the magnetization process. Square like hysteresis loop and relatively small saturation field is observed in Co/glass system. The coercive field of 100 nm Co on glass is only 50 Oe. This is due to the fact that the magnetization is dominated by the in-plane anisotropy field. The presence of interfacial anisotropy field in Co/Si (001) system is responsible for large saturation field and hence a small values of squareness of the hysteresis loop. Both the interfacial and surface anisotropy fields influence the shape of the hysteresis loop. Therefore, it is evident from the explanation curve that the resultant field due to the interfacial anisotropy and surface induced anisotropy fields is comparable with in-plane anisotropy field. The coercive field of Co thin film on GaAs (001) is enhanced due to the special interaction between Co and GaAs (001) substrate. Therefore, it is evident from the experimental observation that the magnetic properties like coercive field, squareness and saturation field can be modulated by surface roughness and interface induced anisotropy fields.

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