The magnetic anisotropy of graphene-covered cobalt on silicon carbide

One of the remarkable properties of graphene is its high spin diffusion length that is due to a weak spin-orbit coupling. This makes graphene a promising spin-transport material to be implemented in spintronic devices [1]. Besides that, graphene has an impact on the magnetic anisotropy of thin magnetic films and can lead to chiral spin textures [2,3]. Due to effects like these, the magnetic properties of graphene-containing systems have become an active field of research. The interfaces of graphene with room-temperature ferromagnets are particularly interesting. Of these, Ni(111) and Co(0001) are highlighted due to their well-matched lattice constants with respect to the graphene lattice. Here, we investigate the graphene-cobalt interface on a silicon carbide (SiC) substrate, with emphasis on the magnetic anisotropy of the graphene-covered cobalt film.

We chose SiC as a substrate since it is the most promising for the implementation of graphene applications, due to its established use in semiconductor industry. Furthermore, pure SiC is semi-insulating, which overcomes the need to transfer the prepared graphene to an insulating substrate. Graphene on SiC can be prepared by high-temperature annealing of the SiC crystal, which leads to preferential evaporation of the silicon atoms since their vapor pressure with respect to that of carbon is higher by orders of magnitude. The remaining carbon atoms then rearrange into a graphene lattice depending on the preparation conditions.

In this study, we prepared graphene-covered cobalt by means of intercalation. We started with a $(6\sqrt{3}\times6\sqrt{3})R30°$ reconstructed SiC(0001) surface, which is the precursor layer of graphene on SiC [4]. Subsequently, cobalt films were deposited on the $6\sqrt{3}$ reconstructed SiC surface and subjected to a controlled annealing procedure. During annealing, a chemical reaction of the cobalt and the SiC surface converts the $6\sqrt{3}$ structure into a graphene film, which is subsequently intercalated by the cobalt atoms. The intercalation temperature is in the range of 300°C to 600°C depending on the cobalt film thickness, as described in detail in reference [5]. In order to get insight into the magnetic properties, photoemission electron microscopy (PEEM) was employed. The PEEM experiments were carried out at SPring-8 **BL17SU** beamline using the SPELEEM apparatus. The intercalation was verified by photoelectron spectroscopy (XPS) using a spherical sector analyzer (CLAM IV, VG Microtech) located at beamline BL11 at the synchrotron radiation source DELTA, Germany.

Figure 1 shows a PEEM image of a $6\sqrt{3}$ reconstructed SiC sample before cobalt deposition. Since the image was recorded during excitation with ultraviolet light from an Hg lamp, the contrast is dominated by local variations of the sample work function. The wide bright stripes correspond to $6\sqrt{3}$ reconstructed SiC terraces whereas the narrow dark stripes correspond to monolayer graphene inclusions at the step edges.

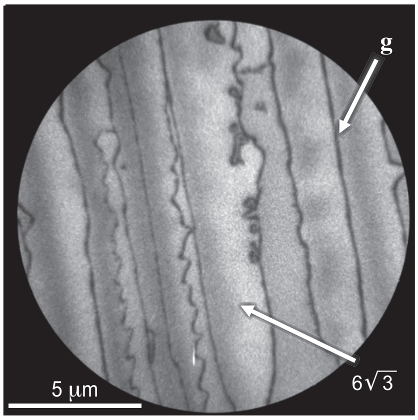

Fig. 1. Ultraviolet-excited PEEM image recorded before cobalt deposition. (g = monolayer graphene)

Figure 2(a) shows an XPS spectrum recorded before cobalt deposition. It consists of four chemically shifted components, which correspond to the $6\sqrt{3}$ reconstructed terraces (components S1 and S2), to the graphene monolayer inclusions at the step edges (component G), and to the bulk SiC bonding (component SiC). After deposition and annealing of a 0.4 nm thick cobalt film, the XPS spectrum is significantly changed, as shown in Fig. 2(b). In particular, the G-component is increased which relates to a partial transformation of the $6\sqrt{3}$ reconstructed surface into a graphene-covered surface. Figure 2(c) shows the XPS spectrum recorded after the deposition and annealing of 3.0 nm cobalt. Here, only one asymmetric graphene-related component remains. Therefore, at high film thickness the $6\sqrt{3}$ reconstruction is fully converted into a graphene-covered surface.

The magnetic properties of the cobalt-intercalated samples with different film thicknesses were investigated using PEEM images with magnetic contrast, obtained by utilizing the X-ray magnetic circular dichroism (XMCD) at the Co L_3-edge. For each film thickness, two images corresponding to 90°-rotated synchrotron radiation incidence direction are shown. Comparing the two images, the preferred magnetization axis can be determined. In particular, it can be determined whether a perpendicular or in-plane magnetic anisotropy is present. For a perpendicular magnetization, no significant contrast change is expected upon sample rotation, whereas the opposite is expected for an in-plane magnetization.

Figures 3(a) and 3(b) show the resulting images for a 1.1 nm thick cobalt film. Clearly, only the regions near the step edges are magnetic. In contrast, for 1.5 nm and 3.0 nm thick cobalt films, the whole surface is magnetic, as shown in Figs. 3(c–f). In both cases, the contrast change upon sample rotation indicates that the magnetization is mostly in the sample plane. Furthermore, it becomes clear that the magnetic domains favorably align parallel or anti-parallel to the substrate step edges, as visible in Figs. 3(c) and 3(e). Therefore, the step edges introduce a significant magnetic anisotropy forcing the magnetization in the sample surface. It is expected that the magnetic anisotropy can be tuned by a modification of the step heights, which is viable through changes to the SiC heating process.

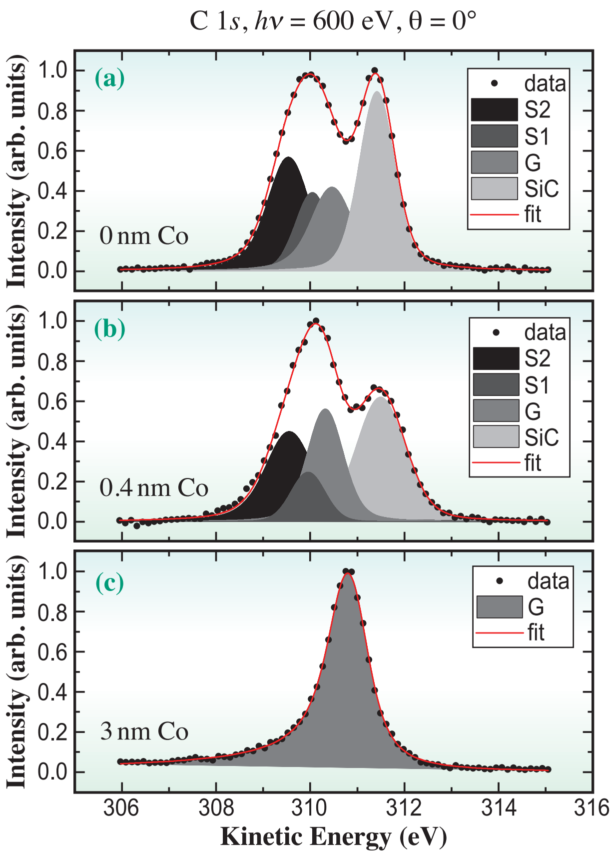

Fig. 2. XPS spectra taken at normal emission: before cobalt deposition **(a)**, after deposition and annealing of 0.4 nm **(b)**, and 3.0 nm **(c)** thick cobalt films.

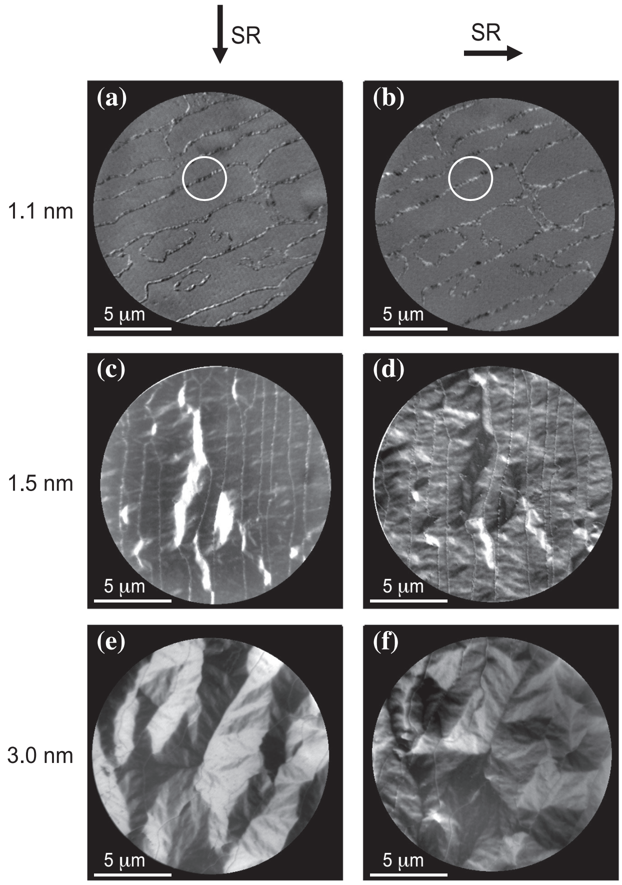

Fig. 3. XMCD-PEEM images with magnetic contrast recorded after cobalt intercalation. The arrows indicate the incidence direction of the synchrotron radiation (SR).

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