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Observation of magnetization alignment switching in $Fe_3Si/FeSi_2$ artificial lattices by polarized neutron reflection

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One of the most powerful and reliable methods to directly observe the switching of interlayer coupling magnetization in multilayer films is polarized neutron reflection. In this study, polarized neutron reflection was employed for artificial lattices comprising alternately accumulated ferromagnetic Fe_3Si and semiconducting $FeSi_2$ layers prepared by facing-targets direct-current sputtering. The switching of interlayer coupling magnetizations was directly observed, which was well consistent with that expected form the magnetization curves.

1. Introduction

The switching of interlayer coupling magnetization in artificial lattices and trilayered films comprising ferromagnetic metal and non-magnetic materials layers is one of the most important trigger in spintronics for inducing spin-dependent physical phenomena such as giant magnetoresistance (GMR) effect [1,2] and tunnel magnetoresistance (TMR) effect [3-8], because the scattering of polarized carriers is changed by the magnetization switching. As a practical example using the switching, there are magnetic heads for hard disks and magnetoresistive random access memory (MRAM). Non-magnetic metal and insulating layers are employed for GMR and TMR elements, respevtively.

We have progress a research on hetero-structural artificial lattices comprising semiconducting $FeSi_2$ spacer layers and ferromagnetic Fe_3Si layers [9-16]. Thus far, we have fabricated $Fe_3Si/FeSi_2$ artificial lattices, wherein the first Fe_3Si layer is epitaxially grown on Si (111) substrates and its orientation is kept to the upper layer across the $FeSi_2$ layers [10]. Owing to the highly-oriented Fe_3Si layers, an extremely strong interlayer coupling is induced across the $FeSi_2$ layers. We have demonstrated an oscillational change in the interlayer coupling for the thickness of $FeSi_2$ spacers from the magnetization curves [9]. Although the shape of magnetization curves is affected by the magnetic properties of ferromagnetic layers, such as the magnetic anisotropy and domain structure, the magnetization alignment switching has been identified from not only the magnetization curves but also other supplemental data such as magnetoresistance curves.

In addition, for the same structural films, we have found that the interlayer coupling is temperature-dependently changed [15] and switched by the injection of current [13,16]. For the former case, the results of magnetoresistance curves are unavailable for the consideration of magnetization alignment switching, since the electrical conductivity of semiconducting $FeSi_2$ layers steeply changes with decreasing temperature and the temperature-dependence of the magnetoresistance curves is complicated. For the latter case, although the magnetization alignment switching is considered mainly from the hysteresis of the electrical resistance against the injection current, the electrical resistance of the semiconducting $FeSi_2$ is sensitively affected by Joules' heat accompanied by the injected current. A direct measurement of the magnetization alignment switching is indispensable for identifying conclusively.

We have never obtained the direct evidences that prove the magnetization switching in their elements. One of the most conclusive methods for directly proving the magnetization alignment switching is polarized neutron reflection [17,18]. This method has ever employed for proving magnetization alignment switching in GMR metallic junctions comprising ferromagnetic metal/nonmagnetic metal layers and TMR junctions comprising ferromagnetic metal/insulator layers. On the other hand, there have been few reports directly proving magnetization switching in junctions comprising ferromagnetic metal/semiconductor layers thus far. In this work, we employed polarized neutron reflection to directly detect the magnetization switching of $Fe_3Si/FeSi_2$ artificial lattices. This paper reports the observation of the magnetization switching by applying magnetic fields.

2. Experimental procedure

$[Fe_3Si/FeSi_2]_{20}$ artificial lattices comprising the Fe_3Si layers with a thickness of 24 Å and $FeSi_2$ layers with thickness of 7.3 Å were deposited on n-type Si(111) substrates with a specific resistance of 1000 - 4000 Ω·cm, which were produced by a floating zone method. The deposition was carried out at a substrate temperature of 300 °C by facing targets direct-current sputtering (FTDCS) using Fe_3Si and $FeSi_2$ alloy targets (4N) with atomic ratios of Fe/Si = 3:1 and 1:2, respectively. The Si(111) substrates were dipped in 5% HF solution and rinsed in deionized water before they were set into the chamber. The base pressure was lower than 2×10^{-5} Pa and the film deposition was performed at 1.33×10^{-1} Pa. The deposition rates of Fe_3Si and $FeSi_2$ layers were 0.62 and 0.21 nm/min, respectively.

The layered and crystalline structures were evaluated by X-ray diffraction (XRD) using Cu $K\alpha$ radiation. The magnetization curves were measured using a vibrating sample magnetometer (VSM). The polarized neutron reflection profiles were measured by SUIREN at JRR-3 in Japan Atomic Energy Agency (JAEA). In both VSM and polarized neutron reflectivity measurements, external magnetic fields were applied in the in-plane direction of the sample.

3. Results and discussion

The typical low-angle X-ray diffraction pattern of a $[Fe_3Si/FeSi_2]_{20}$ artificial lattice is shown in Fig. 1. Bragg peaks due to the periodically Fe_3Si layers were observed. For other samples, the Bragg peaks due to the periodically layered structure were observed, similarly. The periodicity, which corresponded to the total thickness of the Fe_3Si and $FeSi_2$ single layers, was in agreement within an error of ±1.5 Å with the total thickness of 25 Å for the Fe_3Si single layer and X Å for the $FeSi_2$, which was estimated from the deposition rate and time. The TEM image of the artificial lattice is shown in the inset of Fig. 1. The bright and dark layers correspond to the Fe_3Si and $FeSi_2$ layers in the TEM image, respectively. The multilayered structure with sharp interfaces was confirmed.

The magnetization curve of $[Fe_3Si(24\ Å)/FeSi_2(7.3\ Å)]_{20}$ artificial lattices is shown in Fig. 2. This magnetization curve shows that antiferromagnetic (AF) interlayer coupling was induced between ferromagnetic Fe_3Si layers. The saturation field (H_s) is 8 kOe.

In order to directly confirm the formation of AF coupling and the switching of magnetization alignment from anti-parallel to parallel by applying magnetic fields, polarized neutron reflection was examined for $[Fe_3Si(24\ Å)/FeSi_2(7.3\ Å)]_{20}$ artificial lattice with AF coupling at zero magnetic field. Figure 3 shows the polarized neutron reflection profiles of the films, measured at zero and 10 kOe.

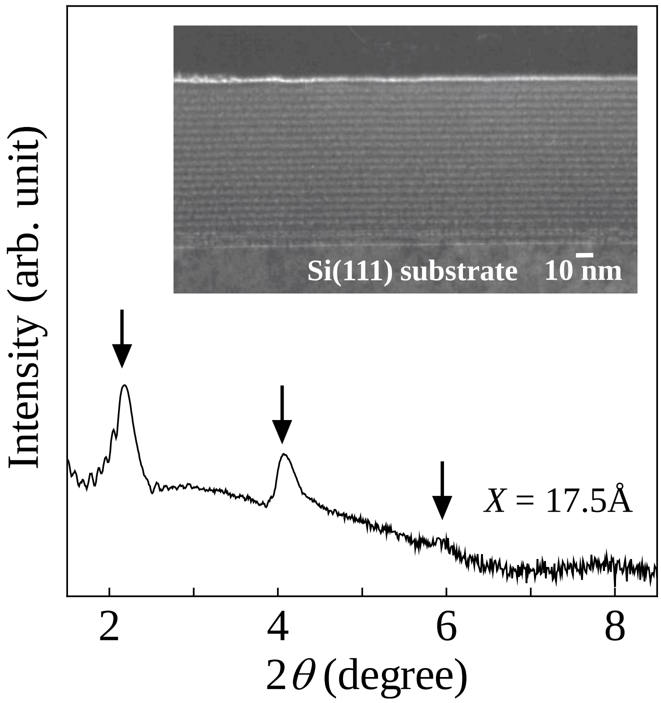

Fig. 1. Low-angle X-ray diffraction pattern of $[Fe_3Si/FeSi_2]_{20}$ artificial lattice. The inset shows cross-sectional TEM image of the artificial lattices.

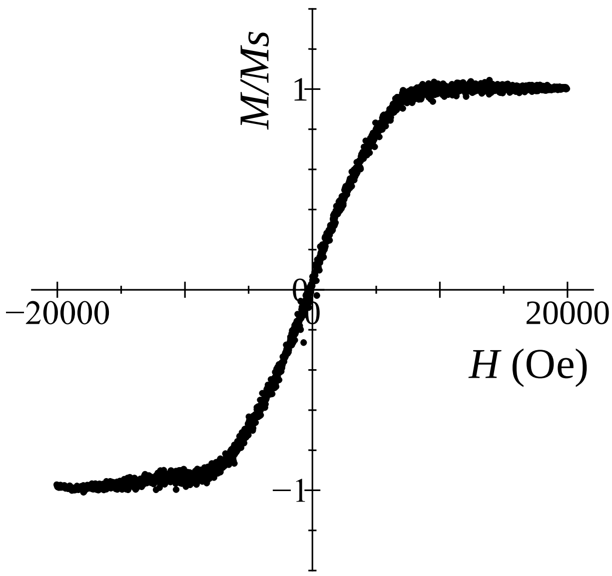

Fig. 2. Magnetization curve of $[Fe_3Si(24\ Å)/FeSi_2(7.3\ Å)]_{20}$ artificial lattices.

Here, the film should have antiparallel and parallel alignments of ferromagnetic layers magnetizations at zero and 10 kOe, respectively. Whereas two peaks are evidently observed at a zero

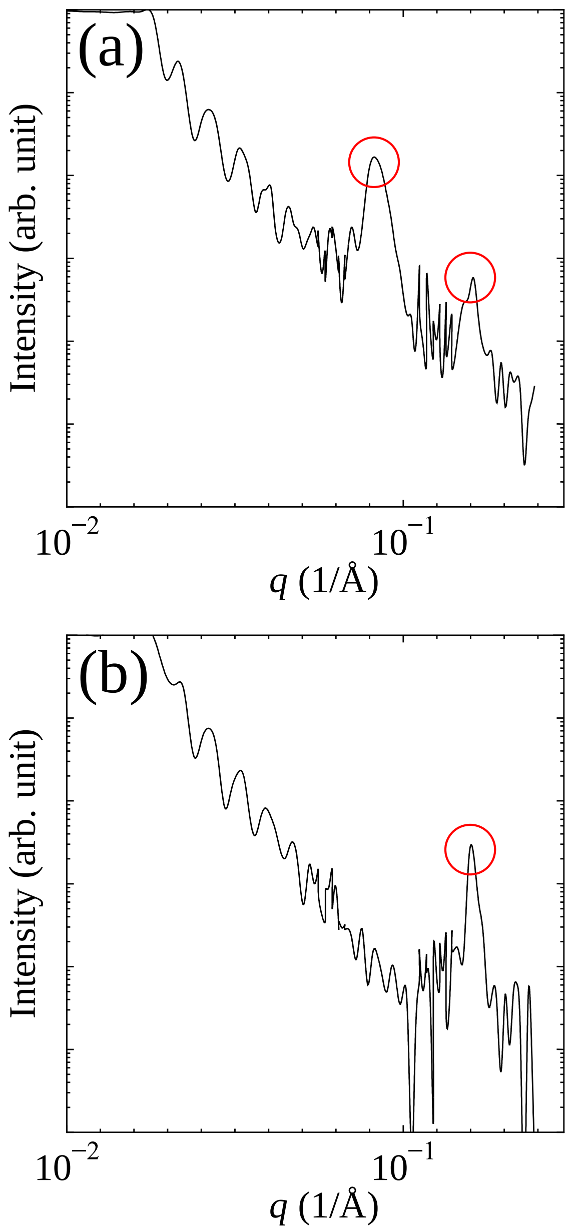

Fig. 3. Polarized neutron reflectivity profiles of [Fe_3Si(24 Å)/$FeSi_2$(7.3 Å)]$_{20}$ artificial lattice measured under magnetic fields of (a) zero and (b) 10 kOe. Two peaks in (a) is attributed to antiparallel alignment of ferromagnetic layers magnetizations induced by AF coupling, while single peak in (b) is due to the parallel alignment.

magnetic field, a single peak is observed at 10 kOe. The additional peak observed at the zero magnetic field is attributed to the antiparallel alignment of magnetizations induced by AF coupling, and the disappearance of its peak at 10 kOe indicates that the magnetization alignment become parallel. The magnetization switching was observed as expected from the results of magnetization curves.

4. Conclusion

Polarized neutron reflection was applied for observing the magnetization switching in $Fe_3Si/FeSi_2$ artificial lattices. The spectroscopic results evidently exhibited a change in the magnetization alignment from antiparallel to parallel by applying a magnetic field, which was in good agreement with the magnetization alignment change expected from the results of the magnetization curves. Polarized neutron reflection was applied for $Fe_3Si/FeSi_2$ heterostructural artificial lattices for the first time to our knowledge and its availability for observing the switching of magnetization alignment was experimentally demonstrated.

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