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Magnetic properties of epitaxial Fe/MgO structures on Si(100)

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A B S T R A C T

The magnetic properties of epitaxial Fe/MgO structures on Si(100) substrates are investigated over an Fe thickness range of 2–20 nm. Superparamagnetic behavior is observed at an Fe thickness of 2 nm, indicating that no continuous Fe thin film is formed. At Fe thicknesses of 5 nm and higher, a continuous two-dimensional layered structure is formed, which has a dominant epitaxial relationship of Fe[010](100)//MgO[01$\bar{1}$](100)//Si[01$\bar{1}$](100) and a minor portion of Fe[010](100)//MgO[010](100)//Si[01$\bar{1}$](100). This structural feature is echoed by a four-fold magnetic anisotropy in the film plane, and this tendency increases with increasing Fe thickness. The strength of the first-order cubic magnetocrystalline anisotropy, which can only be extracted from the structures, is in the range of 3.87×10^5–4.04×10^5 erg/cm^3, weaker than that of bulk Fe (4.8×10^5 erg/cm^3).

1. Introduction

Because of the conductivity mismatch between a ferromagnetic metal (FM) and a semiconductor (SC), it is difficult to inject spin-polarized electrons from FM to SC, which is a key process in spintronic applications. This problem can be solved by inserting a tunneling barrier such as Al_2O_3, SiO_2, or MgO between the FM and SC [1–3]. Among known insulators, MgO is particularly interesting owing to its role as a spin filter, allowing for higher spin injection efficiency [4,5]. Furthermore, MgO plays a structural role by reducing intermixing between the FM and SC [6,7]. Epitaxially grown stacks of Fe/MgO/GaAs have been frequently investigated in the past, mainly because of the small lattice mismatch (0.6%) between MgO and GaAs with a lattice registry of 4 MgO/3 GaAs [8]. Recently, Si has attracted much attention in spintronic applications because of its dominant position in current electronics. A spin device consisting of Fe/MgO/Si can easily be combined with conventional Si-based metal-oxide SC field-effect transistors. Si also has a long spin lifetime (approximately 1.3 ns) [9–11] due to its weak spin-orbit coupling, aiding in the detection of strong spin signals even at room temperature [12]. These are the primary motivations behind the frequent studies of Fe/MgO/Si systems, with both their structural [13–15] and spin transport properties [10–17] having been reported. However, the magnetic properties of such systems have rarely been discussed. In Ref. [13], while the MgO layer was too thick (≥ 20 nm) to inject spins from the FM to the SC, it is still important to understand their magnetic properties as the operation of spin devices typically involves magnetization switching. In this study, both the structural and magnetic properties of Fe/MgO/Si systems with a thin MgO layer (2.3 nm) are investigated, with the main focus being placed on the changes in magnetic properties as a function of Fe thickness.

2. Methods

A Si(100) substrate was cleaned with an ultrasonic cleaner first in acetone and then in methanol. After the cleaning, the native oxide layer formed on the substrate was removed in a buffered hydrofluoric acid solution before loading in a cluster molecular-beam epitaxy (MBE) system, composed of two MBE chambers (one for SC and one for metal) and an electron-beam evaporator. The residual surface oxide layer was removed by heating the substrate at 850 °C for 30 min in the semiconductor MBE chamber with a base pressure $\leq 4 \times 10^{-10}$ Torr. The oxide-free Si substrate was transferred to the metal MBE chamber where the epitaxial layers of Fe and MgO were grown at 200 °C. The thickness of MgO was fixed at 2.3 nm, but the Fe layer thickness (t_{Fe}) was varied from 2 to 20 nm (namely, t_{Fe}=2, 5, 7, 10, and 20 nm). This MgO thickness is sufficient to enable structural characterization while being thin enough for efficient spin injection. With regard to the latter, it is worth noting that a small tunnel resistance ($\leq 10^9\ \Omega\ \mu m^2$) was reported in Fe/MgO (2.5 nm)/p-type Si(001), which is within the regime of the classical impedance mismatch [17]. Lastly, a 3-nm-thick Ti layer was added in the electron-beam evaporator chamber

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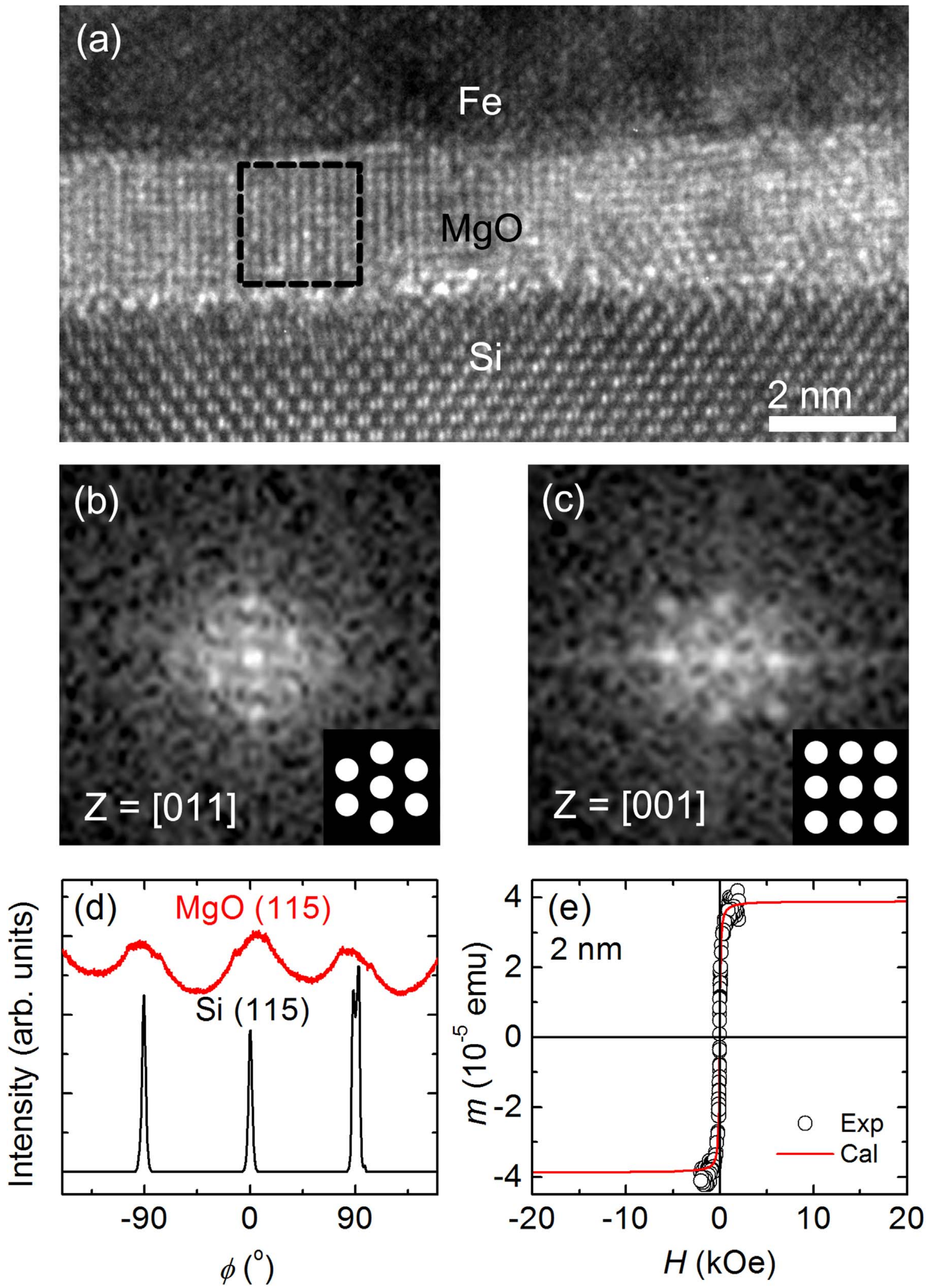

Fig. 1. (a) Cross-sectional HRTEM image of the stack with the structure Fe (5 nm)/MgO (2.3 nm)/Si(100). The dashed rectangle shows the [001] zone axis, whereas the rest of the area in MgO shows the [011] zone axis. The image of the Fe layer is intentionally darkened in order to clearly differentiate the Si and MgO layers. (b) The FFT pattern, which corresponds to the [011] zone axis, indicates an epitaxial relationship of MgO[01$\bar{1}$](100)//Si[01$\bar{1}$](100). The inset shows the reference FFT pattern for the rock salt structure with the same zone axis. (c) The FFT pattern corresponds to the [001] zone axis, indicating an epitaxial relationship of MgO[010](100)//Si[01$\bar{1}$](100). The inset shows the reference FFT pattern for the rock salt structure with the same zone axis. (d) X-ray ϕ-scan diffraction patterns for the stack of Fe (5 nm)/MgO (2.3 nm)/Si(100). (e) Experimental in-plane $m-H$ loop (circles) and the fit using the Langevin function (solid line) for the stack of Fe (2 nm)/MgO (2.3 nm)/Si(100).