



Exchange bias and anisotropy in the Fe/KCoF₃ structure

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Abstract

A new type of ferromagnet/antiferromagnet structure (Fe/KCoF₃) was deposited by molecular beam epitaxy. Unidirectional and uniaxial anisotropies of 5.1 and 3.4 kA/m were measured at 23 K using ferromagnetic resonance. Magnetization measurements at 5 K showed a hysteresis loop shift of 6 kA/m due to exchange bias. Significant enhancement of four-fold anisotropy was found at low temperatures in the samples with polycrystalline KCoF₃ structure. © 2002 Elsevier Science B.V. All rights reserved.

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When a thin ferromagnet is exchange coupled to an antiferromagnet, the bilayer can have a hysteresis curve characterized by an increased coercivity, and a shift in the hysteresis curve, known as exchange biasing. The phenomenon has been of interest, partly because of the possible technological applications. Although this exchange bias was first observed over 40 years ago, understanding the effect has proven to be problematic [1]. Most of the research has focused on antiferromagnets with large magnetocrystalline anisotropy. In contrast we explore here a ferromagnet/antiferromagnet combination where the magnetocrystalline anisotropy in the antiferromagnet is small.

We have developed a new type of ferromagnet/antiferromagnet structure consisting of iron and potassium cobalt fluoride, Fe/KCoF₃, using molecular beam epitaxy (MBE). Neither the properties of this system nor the techniques for its fabrication have been reported in the literature. The main objective of our studies was to

investigate the exchange bias in ferromagnet/antiferromagnet structures with the latter exhibiting low magnetocrystalline anisotropy. We have used magnetometer and ferromagnetic resonance (FMR) measurements to determine the magnetic properties of our structures. As in previous studies [2–4], the FMR allowed us to determine all anisotropies in our system. The magnetic properties of the bilayer structures with both single-crystal and polycrystalline fluoride films and various Fe layer thicknesses are discussed in the paper.

We deposited an Fe seed layer (5 monolayers thick) and a Ag (001) film (30–70 nm thick) on a Ga-terminated GaAs (001) wafer. We monitored the subsequent growth of 10–20 monolayers of Fe on the Ag with a quartz crystal thickness monitor and reflection high-energy electron diffraction (RHEED) intensity oscillations. The RHEED patterns showed that the Fe film was single crystal, body centered cubic, with (001) orientation. We then deposited KCoF₃, with a thickness of 30 nm, onto the Fe film, followed by a 3 nm Au protective layer. To confirm the stoichiometry of the fluoride we used a X-ray diffractometer (XDS 2000, Scintag Inc.) with Cu-K_α radiation. We prepared a 100 nm thick polycrystalline KCoF₃ film grown directly on GaAs. The diffraction pattern clearly indicated the

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presence of the KCoF_3 phase with a lattice constant of 0.407 nm.

KCoF_3 is an antiferromagnet with low magnetocrystalline anisotropy and a Néel temperature of 114 K [5,6]. Its perovskite structure, with a lattice constant of 0.407 nm [7], almost perfectly matches the Fe film structure; the lattice mismatch is $<0.25\%$. The Fe atoms occupy four-fold sites on the (001) surface of the fluoride. It was possible to grow single-crystal KCoF_3 films on the single-crystal Fe film at 390–420 K, as determined by sharp RHEED patterns. However, deposition at 300 K resulted in polycrystalline KCoF_3 films.

It is commonly known that the exchange interaction between thin ferromagnetic and antiferromagnetic films changes their respective magnetic properties [8]. In particular, exchange bias results in a shift of magnetic hysteresis of the ferromagnet. We find this signature in our samples, with the largest magnetization loop shift of 6 kA/m (Fig. 1) for a 1.6 nm Fe layer and polycrystalline fluoride, measured at 5 K in a magnetometer based on a superconducting quantum interference device (SQUID). We cooled the sample in a magnetic field of 7 T oriented along the hard anisotropy axis [1 1 0] of the Fe. A similar sample with a 2.4 nm Fe layer showed a loop shift of 3.6 kA/m.

FMR measurements also indicated the exchange bias between the ferromagnet and the antiferromagnet. We used an FMR system operating at 24 GHz from 23 to 400 K to measure the in-plane anisotropy in the Fe/ KCoF_3 structures. Fig. 2 shows the angular dependences of the FMR field for a 1.6 nm thick Fe layer at 23 and 300 K. We determined the anisotropy fields by fitting the FMR equations [9] to the curves. This provided values of the four-fold magnetocrystalline anisotropy field (H_{4f}), the uniaxial anisotropy field (H_{UA}) and the unidirectional anisotropy field (H_{UD}).

We found only one anisotropy component for (1.6 nm)Fe/(30 nm) KCoF_3 : H_{4f} was 35 kA/m at 300 K; it was 77.4 kA/m at 23 K after zero-field cooling (Fig. 2).

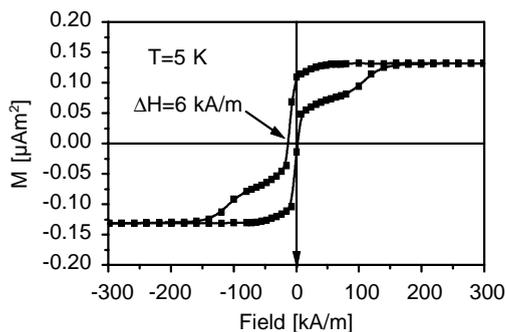


Fig. 1. Magnetization hysteresis loop measured at 5 K along the hard anisotropy axis for the 1.6 nm Fe/ KCoF_3 (polycrystal) bilayer cooled in a magnetic field oriented along the hard axis.

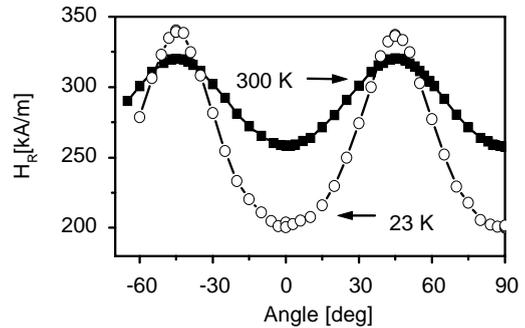


Fig. 2. Angular dependence of the FMR fields measured at 300 and 23 K (zero-field cooled) for the 1.6 nm Fe/ KCoF_3 (polycrystal) bilayer.

However, for the same sample cooled in a magnetic field $H = 400$ kA/m oriented along the easy anisotropy axis [1 0 0] of Fe, we measured both $H_{UA} = 3.4$ kA/m and $H_{UD} = 5.1$ kA/m in addition to the H_{4f} . For the sample with a 1.9 nm thick Fe layer and single-crystal fluoride, H_{UA} was about 3.2 kA/m and $H_{UD} = 1.6$ kA/m. This value of H_{UD} is lower than that for the sample with an even thicker Fe layer of 2.4 nm and polycrystalline fluoride. It is plausible that the uniaxial in-plane anisotropy is controlled by structural defects at the interface between the single-crystal Fe film and the polycrystalline KCoF_3 .

The amount of angular variation of the resonant field in Fig. 2 and the resultant four-fold anisotropy almost double at low temperatures compared to room temperature. The temperature dependence of the magnetocrystalline anisotropy for the Fe/ KCoF_3 structure was significantly different from that expected for single-crystal BCC-Fe films or bulk.

The uniaxial and unidirectional anisotropies were small compared to the four-fold anisotropy, and therefore we were able to calculate the temperature dependence of the four-fold anisotropy field from the temperature measurements of the resonant fields for the easy and hard anisotropy axes. Fig. 3 shows the temperature dependence of four-fold anisotropy fields for three different samples: (a) 1.6 nm Fe/ KCoF_3 (polycrystalline), (b) 1.9 nm Fe with a 3 nm Au capping layer, and (c) 1.9 nm Fe/ KCoF_3 (single crystal). Curves (b) and (c) in Fig. 3 are essentially parallel; the difference between the initial values at room temperature may arise from different surface anisotropies at the interfaces between Fe and Au, and Fe and Fe/ KCoF_3 . Curve (a) follows curves (b) and (c) only at temperatures above 180 K; at low temperatures it demonstrates significant deviation that results in an enhanced four-fold anisotropy.

The low temperature enhancement of the magnetocrystalline anisotropy appears to be related to the polycrystalline structure of the KCoF_3 rather than to the variation of the anisotropy with the Fe film

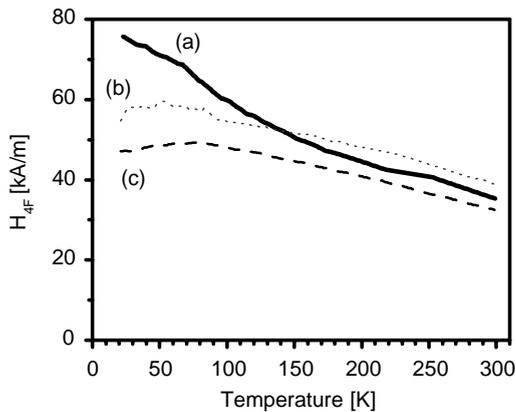


Fig. 3. Temperature dependence of the four-fold anisotropy fields for three different samples: (a) 1.6 nm Fe/KCoF₃ (polycrystal) bilayer (solid line), (b) single-crystal 1.9 nm BCC-Fe (dotted line), and (c) 1.9 nm Fe/KCoF₃ (single-crystal) bilayer.

thickness. Fe (001) films exhibit an increasing four-fold anisotropy with increasing layer thickness; it rises by a factor of 4 when the number of atomic layers increases from 5 to 17 [10]. Previous studies have shown that the in-plane anisotropy fields of an Fe film with a thickness of 1.5 nm and a Au capping layer are 26.1 kA/m at room temperature and 36.6 kA/m at 77 K [11], which are substantially lower than the values of 35 and 65 kA/m measured at the same temperatures in the sample with nearly the same Fe thickness and polycrystalline fluoride. Thus, in addition to the enhanced temperature coefficient of the four-fold anisotropy at low temperatures, room temperature anisotropy fields are considerably larger in the structures with polycrystalline KCoF₃ compared to those in single Fe films or in Fe/KCoF₃ single-crystal bilayers.

The structures with polycrystalline fluoride show a four-fold anisotropy dependence on Fe layer thickness that is opposite to that observed in an Fe film. In the structures with polycrystalline fluoride, the four-fold anisotropy decreases with increasing Fe film thickness, especially at low temperatures, with a value close to that of Fe capped with Au. For example, the anisotropy measurements of the bilayer with 2.4 nm Fe and polycrystalline KCoF₃ show that the four-fold anisotropy field at 77 K decreased to 57.3 kA/m compared to 65.7 kA/m for the similar sample with 1.6 nm thick Fe. This behavior is characteristic of surface-related phenomena; their contributions to anisotropy are inversely proportional to film thickness. Therefore, we believe that interfacial effects are responsible for the enhance-

ment of the anisotropy. For example, the BCC phase modification and surface reconstruction of ultrathin Ni films were important for large enhancement of the in-plane anisotropy of Fe films deposited onto Ni films [12]. A similar mechanism may explain the enhanced anisotropy in our system due to structural defects in the growth of the polycrystalline fluoride on the BCC-Fe crystal. A magnetoelastic contribution to the anisotropy originating from the surface magnetostriction is another possible source of enhancement of the anisotropy; however, more detailed structural and magnetic studies would be necessary to confirm this.

The crystalline quality of the fluoride film, as determined by RHEED, has a dominant effect on the magnetic properties of the Fe. The modified microstructure of the interface between Fe and KCoF₃ for polycrystalline fluoride, compared to a perfect lattice match for single-crystal fluoride, leads to the enhancement of unidirectional and four-fold anisotropies.

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