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Magnetic properties of epitaxial NiFe/Cu/Co spin-valve structures on GaAs(001)

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Cu(50 Å)/NiFe(60 Å)/Cu(60 Å)/Co(20 Å) epitaxial spin-valve structures were grown on GaAs(001) substrates by molecular-beam epitaxy at room temperature. *In situ* reflection high-energy electron diffraction measurements indicate the stabilization of the bcc-Co(001) phase on 1×1 unreconstructed GaAs(001) for thicknesses up to 20 Å and the epitaxial growth of the fcc-Cu(001) spacer layer and fcc-FeNi(001) top magnetic layer. Magneto-optical Kerr effect and Brillouin light-scattering measurements of the composite structure showed that a fourfold cubic anisotropy is present but a twofold anisotropy also occurs directed along the ⟨110⟩ axes. The easy cubic axes are directed along the ⟨100⟩ axes, which implies that the cubic anisotropy constant K_l for bcc-Co is positive. The magnetic anisotropy of the bcc-Co layer has a striking influence on the magnetoresistance characteristics which were found to be angular dependent. A simulation of this mixed anisotropy behavior yields quantitative agreement with the experimental results. [S0021-8979(00)47808-4]

Hybrid magnetic–semiconductor structures are of great interest recently due to their attractive possibilities in device and sensor applications. Several single-element or binary alloy systems have been extensively studied such as Fe/GaAs,[1–6] Co/GaAs,[7–11] and CoFe/ZnSe.[12] Among these ferromagnet/semiconductor studies, those on single-crystal Co on GaAs have given rise to controversies concerning the structure and magnetic anisotropy properties since the first observations by Prinz.[7]

In this study, epitaxial NiFe/Cu/Co spin-valve structures were fabricated on a GaAs(001) substrate by using molecular-beam epitaxy (MBE) techniques in an UHV chamber. It is the aim of this work to observe the effect of the Co/GaAs interface on the spin-valve magnetic properties. Permalloy does not easily grow epitaxially on GaAs substrates, but bcc Co can be stabilized on GaAs. Large Cu buffer layers have been eliminated which were always used on Si substrates to obtain single-crystal growth. Without this large buffer layer, current shunting effects in the current-in-plane (CIP) geometry can be avoided. Moreover, the Schottky barrier formed at the metal–semiconductor interface has a similar function.[11]

The substrates used were undoped commercial single-crystal GaAs wafers. They were first degreased in acetone then rinsed in isopropanol and finally pull dried in a dry N_2 gas flow before inserting them into the MBE growth chamber. The sample was annealed to $\sim 500\,°C$ for ~ 2 h before being grown at room temperature under ultrahigh vacuum conditions with a base pressure of $\sim 1\times10^{-10}$ mbar. After annealing, the substrates were monitored by *in situ* reflection high-energy electron diffraction (RHEED) and Auger electron spectroscopy (AES). The observed RHEED images were taken with a 15 keV electron gun along the ⟨110⟩ azimuths and show an unreconstructed 1×1 GaAs(001) surface [Fig. 1(a)]. Since the surface is unreconstructed, we are unable to distinguish between the two ⟨110⟩-type directions. The ''spotty'' as opposed to ''streaky'' RHEED images indicate that the sample surface is relatively rough. Only C and a small fraction of O were found in the AES spectra of the GaAs(001) substrate. According to the literature, only the use of ion bombardment could completely remove all detectable contaminants from the GaAs surface.[10]

The spin-valve structure that we grew had a nominal composition as follows: NiFe(60 Å)/Cu(60 Å)/Co(20 Å)/

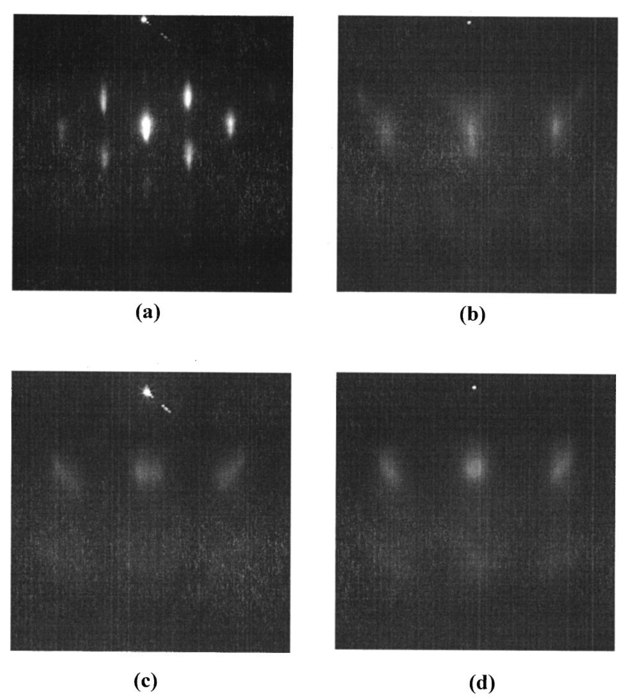

FIG. 1. Series of RHEED patterns taken during the growth of Co/Cu/NiFe multilayers on GaAs(001) along the GaAs ⟨110⟩ azimuth at an incidence angle of ~1° on the surface of (a) GaAs substrate, (b) 20 Å Co/GaAs, (c) 60 Å Cu/Co/GaAs, and (d) 60 Å NiFe/Cu/Co/GaAs.

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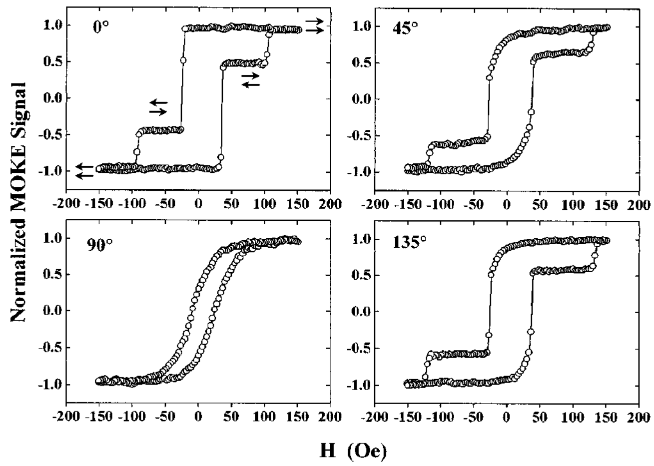

FIG. 2. Hysteresis behavior measured by MOKE along the four principal axes of a sample with the structure Cu/NiFe/Cu/Co/GaAs.

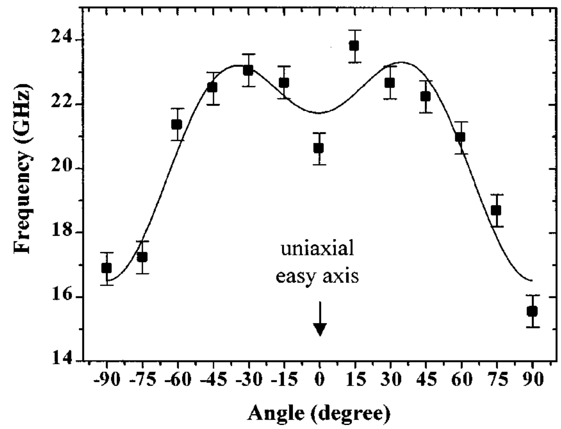

FIG. 3. BLS spin-wave frequencies as a function of the angle between the in-plane applied magnetic field and the uniaxial easy axis for the epitaxial Cu(50 Å)/Co(20 Å)/GaAs(001). The solid line is the simulated fit to the data.

GaAs(001) and a 50 Å Cu capping layer was grown as a protection layer. A separate Cu(50 Å)/Co(20 Å)/GaAs(001) sample was also grown under the same conditions for the Brillouin light-scattering (BLS) measurements. During thin-film growth, *in situ* RHEED measurements, as shown in Figs. 1(b), 1(c), and 1(d), confirm epitaxial growth of the Co bottom layer, Cu spacer layer, and NiFe top magnetic layer. After depositing 20 Å bcc phase Co, the subsequent Cu spacer layer and NiFe top ferromagnetic layer were found to grow fcc but with the ⟨100⟩ axes rotated by 45° with respect to that of the Co to minimize the lattice mismatch. The lattice mismatch between bcc Co(2.82 Å) and GaAs(5.65 Å) is small, ∼0.18%. The epitaxial relationship for this spin-valve structure was thus found to be

$$\mathrm{NiFe}(001)\langle 100\rangle \| \mathrm{Cu}(001)\langle 100\rangle \| \mathrm{Co}(001)\langle 110\rangle \| \mathrm{GaAs} \times (001)\langle 110\rangle.$$

The magnetic properties were characterized using *ex situ* magneto-optical Kerr effect (MOKE) magnetometry. The room-temperature MOKE loops are shown in Fig. 2. Well-defined magnetization configurations can be seen in the hysteresis behavior. The sharp switching and the plateau regions are consistent with ideal spin-valve behavior. The MOKE loops reveal the presence of a fourfold cubic anisotropy but a twofold uniaxial anisotropy also occurs, directed along the substrate ⟨110⟩ axes. The two in-plane ⟨100⟩ axes are found to be equivalent and the global easy axis is directed along one of the $\langle\bar{1}10\rangle$-type directions, which we (arbitrarily) assign as the [110] direction or 0°. The presence of the uniaxial anisotropy complicates the analysis of MOKE loops. As NiFe usually has a negligible contribution to the magnetic anisotropy, it is believed that the Co/GaAs interface induces dominant in-plane uniaxial anisotropy in the films.

BLS measurements on the Cu(50 Å)/Co(20 Å)/GaAs(001) sample were carried out in the standard backscattering geometry. In Fig. 3 the spin-wave frequency of the Daman–Eshbach mode is plotted against the angle between the applied field and the global easy axis. It is clear that the two inequivalent frequency minima along the ⟨110⟩ directions indicate the presence of both uniaxial and cubic anisotropy with the cubic easy axes along the ⟨100⟩ directions. By fitting the data, the ratio of the uniaxial anisotropy to the cubic anisotropy $|K_u/K_l|$ was determined to be 1.3. The BLS observation is consistent with the MOKE result.

Magnetoresistance (MR) measurements were carried out with a standard in-line four-point probe with the current along the global easy axis for Co. The MR results for the spin-valve structure also show the mixture of uniaxial and cubic anisotropy behavior. The MR ratio along the global easy axis was determined to be 0.70% at room temperature and to increase to 2.2% at 10 K. Figures 4(a) and 4(b) show the MR loops taken along the substrate ⟨110⟩ and ⟨100⟩ directions. For comparison, MOKE loops are superimposed on the MR data to show the consistency of the switching field measurements. The MR loops present well-defined plateaus indicating a complete antiparallel alignment. The small magnitude of the MR is most likely due to current shunting effects in the relatively large Cu spacer layer. Figure 4(c) shows the MR ratio of the epitaxial spin valve for the field applied along different principal crystallographic orientations of the GaAs(001). During the angular MR measurements, the probe axis was fixed relative to the GaAs substrate while the field direction was varied. The highest MR amplitude lies along the ⟨100⟩ directions and the smallest MR amplitude occurs along the uniaxial hard-axes directions. This confirms the striking influence of the bcc-Co/GaAs(001) magnetic anisotropy on these spin-valve heterostructures.

There are several possible sources for the origin of the uniaxial anisotropy in the thin Co films: growth-induced anisotropy, strain-induced anisotropy, and interface effects. First, we can rule out of growth-induced anisotropy as the same sample was rotated continuously during growth to suppress any possible growth-induced anisotropy. Second, the lattice mismatch between bcc Co and GaAs(001) is only 0.18% and, therefore, for a strain-induced anisotropy to occur, a very large surface magnetoelastic constant would be required. We suggest that the interface could also play an important role. According to the explanation by Krebs *et al.*,[2] for the uniaxial magnetic anisotropy in Fe/GaAs, there are two types of GaAs surfaces with either Ga- or As-

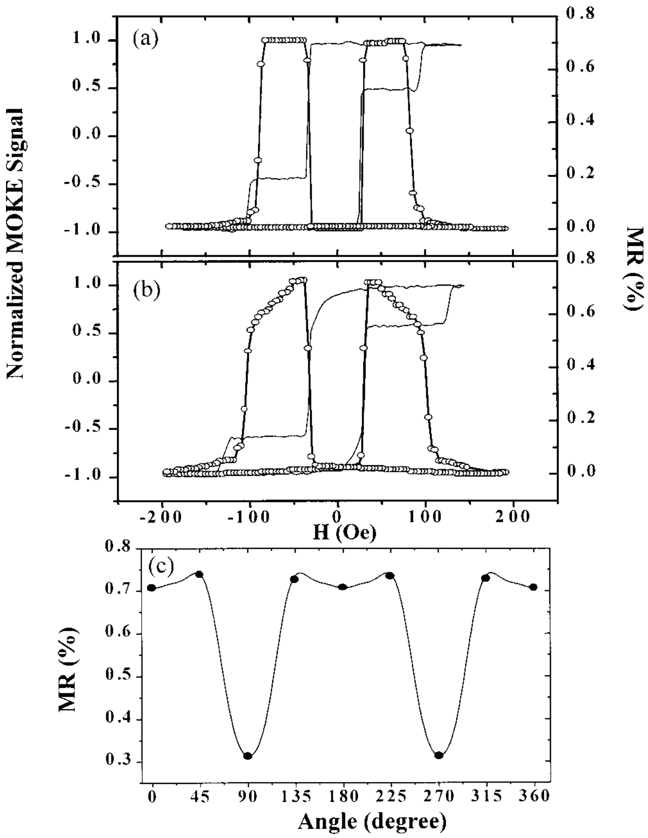

FIG. 4. MR measurements along the (a) ⟨110⟩ and (b) ⟨010⟩ directions. (c) Angular-dependent MR ratio of the epitaxial NiFe/Cu/Co/GaAs(001) spin-valve structure. All data were taken at room temperature.

rich surface atoms. The type of surface depends on the substrate preparations and growth conditions.[4–6] Each surface atom has its bond oriented along only the [110] or [110] direction depending on either the Ga or As surface. In this work, high-temperature annealing was used to desorb the As cap layer, leaving a Ga-rich surface. The asymmetry in the direction of the Co–Ga bonding at the interface is assumed to be responsible for the magnetic inequivalence of the [110] and [110] directions.

A simple model based on coherent rotation can be used to simulate the magnetization response of the epitaxial spin-valve structures grown on GaAs(001). The energy per unit area of the system can be expressed as

$$\begin{aligned} E = & -t_1\mathbf{M}_1\cdot\mathbf{H} - t_2\mathbf{M}_2\cdot\mathbf{H} + t_1K_{u1}\sin^2[\theta_1-\alpha] \\ & + (t_2K_{c2}/4)\sin^2[2(\theta_2-\alpha)] + t_2K_{u2}\sin^2[\theta_2-\alpha] \\ & - 2A_{12}\cos(\theta_1-\theta_2). \end{aligned} \tag{1}$$

The first two terms represent the Zeeman energy of the magnetic layers, with magnetization $\mathbf{M}$ and thickness t, in an external field $\mathbf{H}$ for the two magnetic layers. K_c and K_u are the cubic and uniaxial anisotropy constants, respectively, for both layers 1 (NiFe) and 2 (Co), each term represents uniaxial or cubic anisotropy energies, where $\theta_{1,2}$ is the magnetization direction in layers 1,2 and α is the Co ⟨100⟩ direction. The final term is the bilinear exchange-coupling term between the two magnetic layers over the Cu interlayer. The

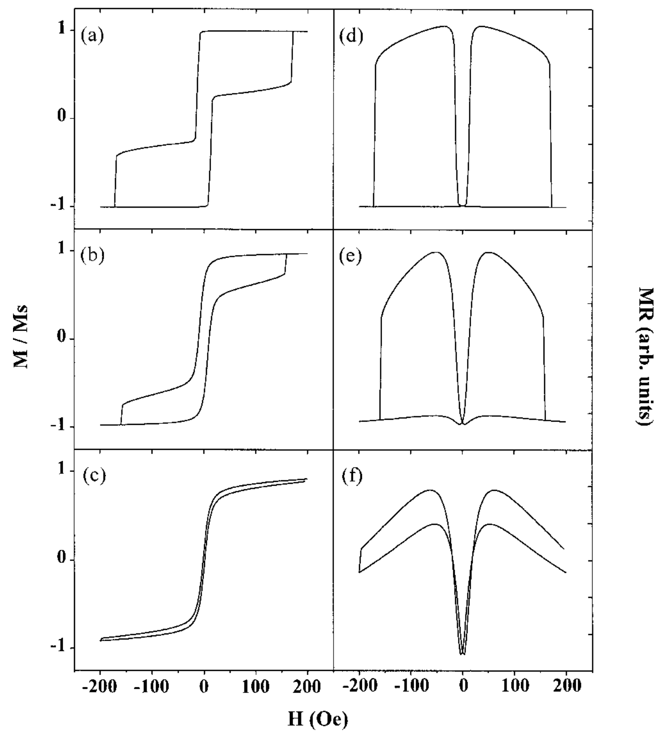

FIG. 5. Simulated hysteresis loops (a), (b), and (c) and MR loops (d), (e), and (f) for Co directions of 0°, 45°, and 90°, respectively.

directions of the magnetization vectors $\mathbf{M}_1$, $\mathbf{M}_2$ can be determined by minimizing the total energy of the system, with respect to θ_1 and θ_2. The simulated hysteresis and MR loops are shown in Fig. 5. This model is, of course, too simple to describe the actual magnetization reversal process precisely, but by using a positive value of K_{c2}, the simulation results give good qualitative agreement with the experimental MOKE and MR loops obtained along different substrate orientations.

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