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Magnetoresistance measurements on Fe/Si and Fe/Ge multilayer thin films

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Abstract

The magnetoresistance and magnetization of multilayer Fe/Si and Fe/Ge films on GaAs were measured simultaneously as a function of magnetic field along the in-plane [1 1 0] and [1 $\bar{1}$ 0] directions of the Fe. The field induced changes in the magnetoresistance and magnetization for each film are discussed in terms of the exchange coupling between the iron layers, and the thickness of the semiconductor spacer layer. The data show that there is exchange coupling across Ge spacer layers for layer thickness less than 1.2 nm.

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1. Introduction

Over the last few years great interest has been taken in the properties of ultra-thin iron films grown on GaAs substrates [1,2]. For thicknesses below 50 nm, these films have crystalline cubic and uniaxial anisotropy [3]. Studies of multilayer Fe/Si films on GaAs have found that for thin (<1.6 nm) Fe layers, the films have cubic and uniaxial anisotropy as well as a strong exchange coupling across the Si layers [4–6]. This exchange coupling can either be bilinear [7] or biquadratic [8]. For the bilinear exchange, the layers are coupled antiferromagnetically, while for the biquadratic exchange the layers are coupled at 90°. From previous work on multilayer Fe/Ge films on GaAs, the exchange coupling is weaker than for Fe/Si films, and strongly dependent on the thickness of the Ge layers [9].

The magnetoresistance of a multilayer film is known to scale with the cosine of the angle θ between adjacent layers' magnetizations [10]. Thus, the magnetoresistance ratio is given by [11]

$$\frac{\Delta R}{R_s} = \frac{R - R_s}{R_s} = \frac{R_0 - R_s}{R_s}\frac{(1-\cos^2\theta)}{(1-\cos^2\theta_0)}, \tag{1}$$

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where R_s is the resistance at saturation ($H = H_s$ and $\theta = 0$), R_0 is the resistance at $H = 0$, $2\theta_0$ is the angle between the magnetizations at $H = 0$. The net magnetization of the film is $M = M_s \cos\theta$. If the coupling between the layers is bilinear, i.e. antiferromagnetic alignment, then $2\theta_0 = 180^\circ$ and Eq. (1) becomes

$$\frac{\Delta R}{R_s} = \left(\frac{R_0 - R_s}{R_s}\right)\left(1 - \left(\frac{M}{M_s}\right)^2\right),$$

$$1 - \frac{R - R_s}{R_0 - R_s} = \left(\frac{M}{M_s}\right)^2. \quad (2)$$

While if the coupling is biquadratic, then $2\theta_0 = 90^\circ$, and the change in resistance is

$$\frac{\Delta R}{R_0 - R_s} = 2\left(1 - \left(\frac{M}{M_s}\right)^2\right).$$

Using Eq. (2) the magnetization, magnetoresistance and exchange coupling of multilayer Fe/Ge and Fe/Si films can be investigated.

2. Experimental

The multilayer films were grown by DC sputter deposition, which is described elsewhere [12]. All three films were grown on GaAs substrates, so that the $[1\bar{1}0]$ direction (hard axes of both anisotropies) was along an edge of the film. From X-ray analysis it was determined that each film was a single crystal [13]. The quality of the interface and the degree of interdiffusion between the layers has not been assessed. For all three films the iron layer thickness was 2.5 nm. For film 1, the spacer layer was Si of thickness 1.2 nm. The layers were repeated 23 times, and capped with 7.5 nm Si layer. For films 2 and 3, the spacer layer was Ge, with thickness 1.2 nm for film 2, and 2.0 nm for film 3. For both films the layers were repeated 22 times, and capped with 10 nm of Si.

A MOKE magnetometer has been adapted to simultaneously measure the magnetization and in-plane magnetoresistance of ultra-thin films as a function of magnetic field. The resistance was measured with the current parallel and perpendicular to the field direction, using the van der Pauw [14] method.

3. Results and discussion

Eq. (2) was used as the basis of the analysis. The magnetization was normalized to ±1 at saturation, and the resistance normalized in accordance with the left-hand side of Eq. (2). For film 1 (Fe/1.2 nm Si), the field dependence of the magnetoresistance and magnetization in the low-field regime are directly related as predicted from Eq. (2): see Fig. 1. Hence the layers are antiferromagnetically aligned (bilinear coupling) and for low fields (<100 mT) the magnetization process is pure rotation. This agrees with previous work [9], which investigated the magnetization as a function of the angle between the field and the [1 0 0] axis. In Fig. 1b, the magnetoresistance is symmetric about $B = 0$, while the squared magnetization is not, hence for $B<0$, the magnetization data and magnetoresistance data disagree. The non-symmetric magnetization data is due to the MOKE signal being a function of the angle between the pass plane of the analyzer and the plane of incidence of the laser on the sample [15]. For film 2 (Fe/1.2 nm Ge), for the whole field regime, the field dependence of the magnetoresistance and the magnetization are also directly related, as given by Eq. (2) (Fig. 2); thus again the interlayer coupling is antiferromagnetic. No hysteresis is observed in the magnetization loop along the $[1\bar{1}0]$ direction (Fig. 2b), as the exchanging coupling is bilinear [8]. From Fig. 3 (Fe/2 nm Ge), the field dependence of magnetoresistance and magnetization are not correlated. The magnetoresistance has similar field dependence for both field directions, while the magnetization shows uniaxial anisotropy. We interpret this as indicating a change in the exchange coupling across the Ge layer at this interlayer thickness. The change could either be the exchange coupling becoming ferromagnetic, i.e. adjacent Fe layers aligning in the same direction ($2\theta_0 = 0^\circ$) or no coupling occurring across the Ge layer. The hysteresis observed in the magnetization again is due to the MOKE signal being a function of the

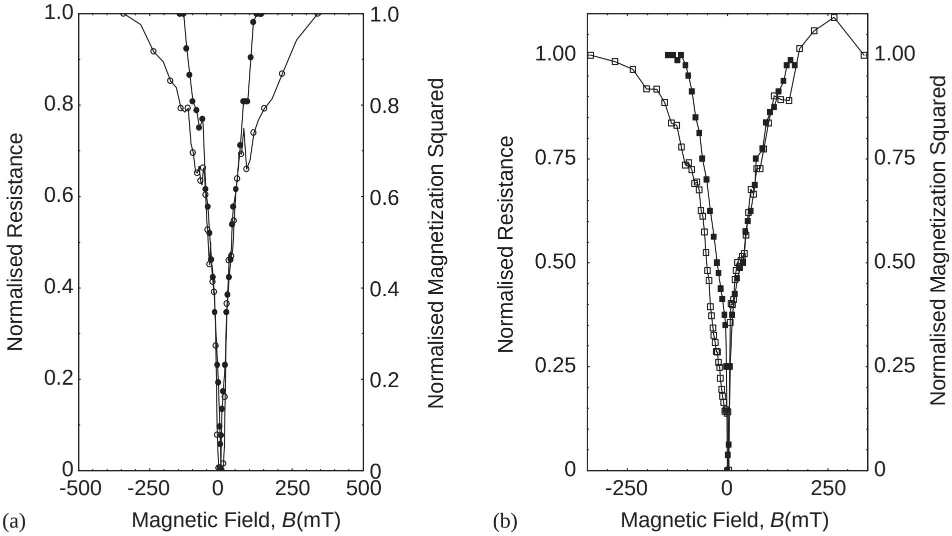

Fig. 1. Normalized magnetoresistance and normalized magnetization squared for film 1 [Fe(2.5 nm)/Si(1.2 nm)], as a function of applied magnetic field, for the field along a, the [1 $\bar{1}$ 0] direction and b, the [1 1 0] direction. The open shapes represent the magnetization data squared, and the closed shapes represent the measured resistance.

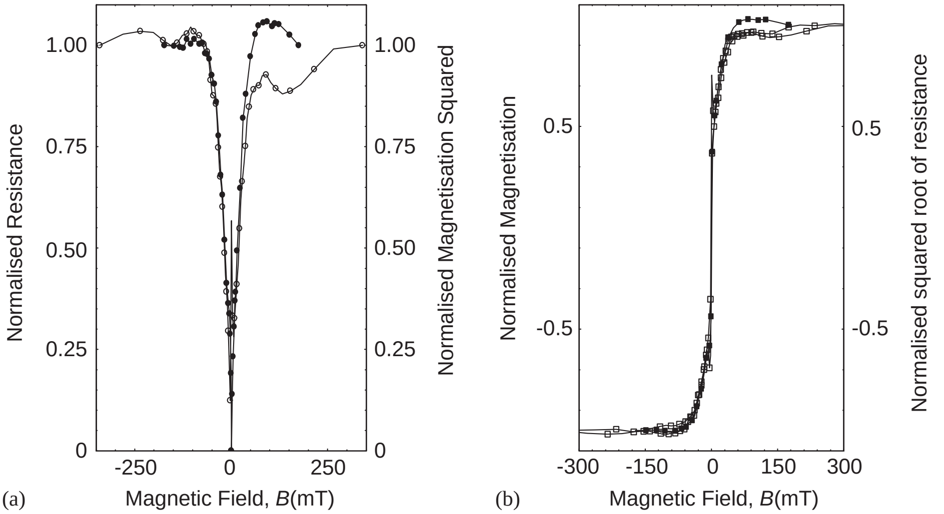

Fig. 2. (a) Normalized magnetoresistance and normalized magnetization squared for film 2 [Fe(2.5 nm)/Ge(1.2 nm)], as a function of applied magnetic field, along the [1 $\bar{1}$ 0] direction. The open shapes represent the normalized magnetization squared data, and the closed shapes represent the measured resistance data. (b) Normalized magnetization and normalized square root of the resistance for film 2, as a function of applied magnetic field, along the [1 $\bar{1}$ 0] direction. The open shapes represent the measured magnetization, and the closed shapes represent the normalised resistance square rooted.

angle between the pass plane of the analyzer and the plane of incidence of the laser on the sample [15].

Comparing the data for film 2 (Fig. 2) and 3 (Fig. 3) shows that the thickness of the Ge spacer layer is important for the exchange interaction between the Fe layers. Previous measurements of Fe/Ge/Fe trilayers with Ge thickness 4 nm, have found no interaction between Fe layers [16]. Bürgler et al. [17] have reported that in Fe/Ge

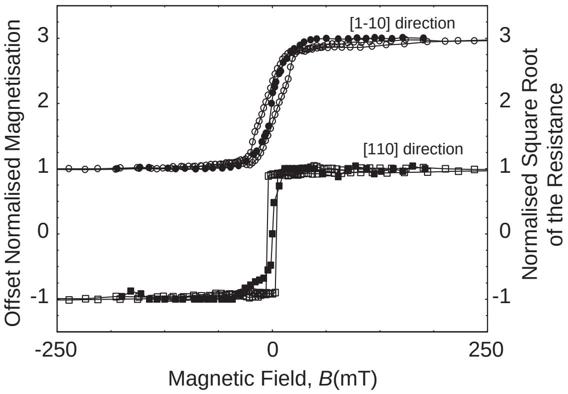

Fig. 3. Normalized magnetization and normalized square root of the resistance for film 3 [Fe(2.5 nm)/Ge(2 nm)], as a function of magnetic field, along the [1 1 0] direction and [1 $\bar{1}$ 0] direction. The open shapes represent the measured magnetization, and the closed shapes represent the magnetoresistance data square rooted.

multilayers there is significant interdiffusion at the interfaces, which they gave as the cause of the suppression of antiferromagnetic coupling in their samples. From Fig. 2, there is an interaction between adjacent Fe layers across 1.2 nm of Ge (film 2), which is antiferromagnetic, hence the coupling is bilinear. The interdiffusion in our samples could be limited compared to Bürgler's samples, hence antiferromagnetic coupling is observed. The magnetization is also pure moment rotation for the whole field regime. For films 1 and 2, cubic and uniaxial anisotropies were observed in the magnetization, while for film 3, only uniaxial anisotropy was measured (Fig. 3). As each Fe layer is 2.5 nm thick, the expected anisotropy would be uniaxial [18], as seen in film 3. The exchange coupling must dominate the intrinsic magnetocrystalline anisotropy in films 1 and 2, but the exchange coupling must be too weak (or zero) for film 3 so that the intrinsic magnetocrystalline anisotropy becomes dominant.

4. Conclusions

Comparing the magnetization and magnetoresistance of multilayer films gives an insight into the exchange coupling which occurs across the non-magnetic spacer layers. When the exchange coupling is bilinear, the adjacent Fe layers align antiferromagnetically, which means the magnetoresistance of the film is proportional to the square of the magnetization. Using this relationship, it was found that there is a strong exchange coupling across the Si spacer layer, there was also an exchange coupling across the 1.2 nm Ge layer. This is the first data to show this exchange coupling for Fe/Ge films. For the thicker Ge layer, the exchange coupling was not bilinear, thus the coupling is sensitive to the thickness of the non-magnetic spacer layer.

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