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Spacer layer properties in antiferromagnetically coupled Fe/Si_xFe_{1-x}

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Abstract

The antiferromagnetically coupled Fe/Si_xFe_{1-x} multilayers deposited in UHV by magnetron sputtering onto oxidized Si wafers for different Fe layer thicknesses $0.3\,nm < d_{Fe} < 4\,nm$ were examined. We showed that both magnetic and electronic properties of the antiferromagnetically coupled Fe/Si Mls are influenced by interfacial mixing between Fe and Si layers. The current–voltage characteristics measured at room temperature, perpendicularly to the multilayer planes allowed us to show the semiconducting character for nominally pure Si layers. We showed that the application of interfacial Co (or Au) thin layers prevented the Fe(Si) interdiffusion into Si(Fe) layers leading to the absence of antiferromagnetic coupling. We found that addition of at least 0.5 nm of Ge in the spacer, introduced either at the Fe/Si interface or in the center of Si spacer destroyed the AF coupling.

Keywords: Magnetic multilayers; Interlayer coupling; Electronic transport

1. Introduction

Metal-semiconductor multilayers (Mls) are extensively studied because of their potential application in electronics. Recently the investigations have been focused on Fe/Si/Fe coupled heterostructures since they show a very strong antiferromagnetic (AF) interlayer coupling [1–6]. In spite of many efforts, the origin of the interlayer coupling in the Fe/Si system has not been clarified. Moreover, it is not well understood how the iron-silicides formation affects the interlayer coupling. Still there is a controversy about the electrical character of the spacer layer; whether it is metallic [2–4] or semiconducting [5,6]. Therefore, the information about the spacer layer properties and its correlation with magnetic properties of this system is of particular interest. The main goal of our study was to examine whether the existence of the AF exchange coupling in Fe/Si_xFe_{1-x} ($x = 1$, 0.66, 0.5) multilayers is related to the intermixing occurring between Fe and Si already during deposition process.

2. Experimental

The $[Fe(3\,nm)/Si_xFe_{1-x}(d_{Si})]_{15} + Fe(3\,nm)$ ($x = 1$, 0.66, 0.50) and $[Fe(d_{Fe})/Si(1.1\,nm)]_{15} + Fe(d_{Fe})$ Mls were deposited by magnetron sputtering in UHV at room temperature onto oxidized Si wafers. The crystalline structure of our samples and their multilayer periodicity were examined using high- and small-angle X-ray diffraction as well as by a high resolution transmission electron microscopy of the cross-section. Magnetic moment measurements were performed after deposition by vibrating sample magnetometer (VSM) at room temperature (RT) whereas the electrical resistance measurements (current in plane, CIP) were done as a function of temperature from 4.2 to 250 K. The perpendicular electronic transport measurements (current perpendicular to the sample plane, CPP) were performed at RT using STM instrument equipped with Au tip with contact area of about $500\,\mu m^2$.

3. Results and discussion

Fig. 1 shows the influence of the spacer layer composition on saturation field H_S and the F_{AF} parameter ($F_{AF} = 1 - M_R/M_S$, where $M_{R(S)}$ denotes remanent (saturation) magnetization). The composition of the spacer layer was chosen to be $x = 0.66$, 0.50 and 1 to simulate the Fe–Si compounds which may be responsible for appearance of the AF coupling ($FeSi_2$, FeSi and Si, respectively). For $x = 0.40$ there is no AF coupling since the spacer layer of this composition is ferromagnetic. As can be seen the strongest interlayer coupling occurs for the spacer layer with nominally pure Si. The interlayer coupling decreases with increasing concentration of Fe in the spacer. In the same manner the F_{AF} parameter behaves (this parameter is usually treated as proportional to the AF coupled fraction of the multilayer). The more detailed study of the influence of x on $H_S(x)$ and $F_{AF}(x)$ are

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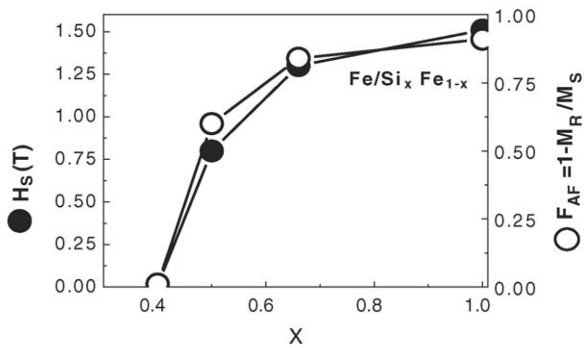

Fig. 1. The influence of the spacer layer composition on saturation field H_S and the F_{AF} parameter of the Fe/Si_xFe_{1-x} Mls with $x = 0.40$, 0.50, 0.66, and 1.

presented in Ref. [1]. Although the strongest AF coupling was found for nominally pure Si, the intermixing process which can occur already during the deposition process cannot be excluded. This process may lead to the appearance of the Fe–Si phases.

Fig. 2 shows the results of the magnetic moment measurements (magnetic moment per surface area, m/S) for Mls with two different Si layer thicknesses as a function of the Fe layer thickness. One can see that, independently of Si layer thickness, about 0.25 nm thick Fe per single Fe/Si interface is magnetically inactive. This result suggests that already during the deposition process the 0.25 nm thick Fe layer dissolves gradually in Si spacer which may initiate the appearance of some structures similar to those of the nonmagnetic Fe–Si phases. We cannot exclude the appearance of the magnetic structures similar to some ferromagnetic Fe–Si phases (e.g., Fe_3Si or Fe_5Si_3). Being ferromagnetic they cannot be responsible for the origin of the AF interlayer coupling (see also Fig. 1). They may, however, control the value of the interlayer coupling due to their diverse saturation magnetization values. The nonmagnetic Fe–Si phases, which can be taken into account to appear at Fe/Si interface are β-$FeSi_2$ (orthorhombic, semiconducting), α-$FeSi_2$ (tetragonal, metallic), ε-FeSi (B20, semiconducting) and FeSi (B2, metallic) [7]. In order to find the electrical properties of the complete multilayer structure the series of Mls with constant Si layer thickness

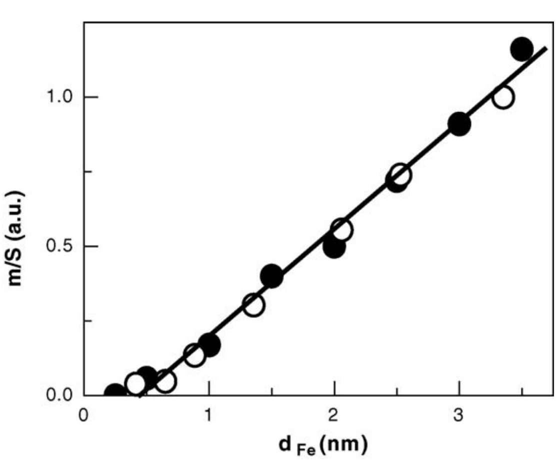

Fig. 2. The magnetic moment per surface area for Fe/Si Mls with two different Si layer thickness (1.1 nm ● and 2.5 nm ○) as a function of the Fe layer thickness.

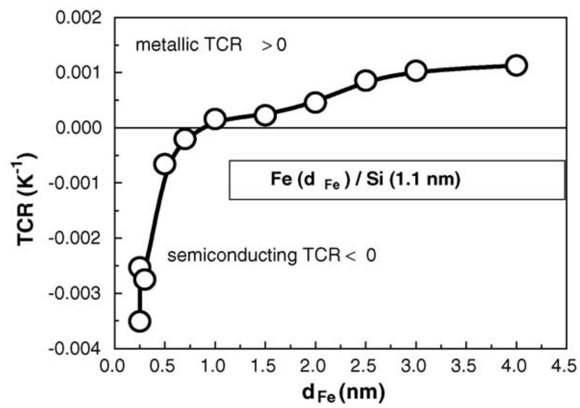

Fig. 3. The temperature coefficient of the resistance (TCR) vs. Fe layer thickness, taken for Fe/Si Mls with $d_{Si} = 1.1$ nm, determined at 250 K.

(1.1 nm) and various d_{Fe} were examined. Fig. 3 shows the temperature coefficient of the resistance (TCR) determined at 250 K ($TCR = (R(T_2) - R(T_1))/(R(T_1)\Delta T)$, where $\Delta T = 4$ K) versus Fe layer thickness. One can see that with the reduction of the Fe layer thickness TCR decreases and below $d_{Fe} \approx 1$ nm changes its sign and becomes negative. Thus, the conductivity changes its character from metallic to semiconducting. We know that almost 0.25 nm of Fe per single Fe/Si interface is magnetically inactive (see Fig. 2), i.e., this Fe thickness is consumed to produce nonmagnetic Fe–Si alloys, both metallic and semiconducting. Thus Fig. 3 shows that the Fe–Si phases which already appear at Fe/Si interfaces during the deposition process may contain mainly nonferromagnetic, semiconducting Fe–Si phases.

In case of Fe/$Si_{0.50}Fe_{0.50}$ and Fe/$Si_{0.66}Fe_{0.33}$ Mls the situation is a little different than in the Fe/Si multilayers. In these structures there is a higher Fe concentration in the spacer layers (50% and 33%, respectively). Therefore, in these Mls, the content of Fe in the spacer layers can increase even more due to the interdiffusion which occurs already during deposition process. The existence of the more diffuse interfaces in the Fe/$Si_{0.50}Fe_{0.50}$ and Fe/$Si_{0.66}Fe_{0.33}$ Mls seems to be confirmed by our small angle X-ray measurements (Fig. 4). Comparing the results obtained for Fe/Si, Fe/$Si_{0.50}Fe_{0.50}$ and Fe/$Si_{0.66}Fe_{0.33}$ Mls we can see that in the latter cases there are less diffraction peaks from the multilayer structure. Therefore, we believe that the interfaces in Fe/$Si_{0.50}Fe_{0.50}$ and Fe/$Si_{0.66}Fe_{0.33}$ Mls may become not only metallic but ferromagnetic as well.

The direct experiment that may confirm the semiconducting character of the spacer layer is the transport measurement for current perpendicular to the sample plane (CPP). Fig. 5 shows the *U–I* characteristic of Fe(3 nm)/Si(1.1 nm) Ml taken at RT. As can be seen the measured characteristic is non-linear proving the semiconducting character of the spacer layers. The measured *U–I* curve can be fitted assuming that the electrical transport is due to tunneling. Applying the Simmons equation [8] we obtain the effective value of tunnel barrier $\phi \approx 1$ eV for whole multilayer (i.e., the individual barrier height is approximately 67 meV) and the barrier width $d_B \approx 0.3$ nm. For the sake of comparison we present also the nonlinear *U–I* characteristic for Fe/$Si_{0.50}Fe_{0.50}$ Ml. The discrepancy between nominal barrier