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Influence of Ge on antiferromagnetic coupling in Fe/Si multilayers

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Magnetic and structural properties of sputtered Fe/Ge, Fe/Ge/Si/Ge and Fe/Si/Ge/Si multilayers were studied. Magnetization measurements revealed the absence of antiferromagnetic coupling for the Ge spacer. It was found that during multilayer deposition, a 0.5 nm thick Fe layer at each Fe/Ge interface became non-ferromagnetic, leading to the formation of antiferromagnetic structures. Mössbauer spectra showed the existence of ferro- and/or antiferromagnetic structures at Fe/Ge interfaces, and ferromagnetic and paramagnetic structures at Fe/Si interfaces. We have found that the substitution of Si by at least 0.5 nm of Ge in the 1.1 nm thick Si spacer led to the disappearance of antiferromagnetic coupling in Fe/Si multilayers.

Key words: *magnetic multilayers; antiferromagnetic coupling; Mössbauer spectroscopy*

1. Introduction

In recent years, a lot of scientific attention has been paid to ferromagnet/semiconductor (FM/SC) layered structures, because of their potential application in spintronics [1–3]. One of the most interesting systems in this field seem to be Fe/Si multilayers (Mls), due to their strong antiferromagnetic (AF) interlayer coupling [1, 3]. Despite many efforts, the origin of AF coupling in this system has not been clarified. Another FM/SC system is Fe/Ge. One could expect that these very similar systems exhibit comparable properties, but experiments revealed no AF coupling at room temperature (RT) in the second structure [1]. In both systems, Fe diffuses into the spacer layer [1, 2]. Therefore, we can surmise that different magnetic and paramagnetic Fe–Si and Fe–Ge phases can be formed. The formation of these phases may play a vital role in the presence or absence of the AF coupling. In this paper, we compare the results of Fe/Si Mls reported previously [3, 4] with Fe/Ge Mls prepared by the same method, and the influence of substituting Si by Ge is discussed.

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2. Experimental

Four series of samples were deposited by magnetron sputtering at RT on oxidized Si substrates: (i) [Fe (3 nm)/Ge (d_{Ge})]$_{15}$ with the Ge layer thickness of $0.5 \leq d_{Ge} \leq 3$ nm, (ii) [Fe (d_{Fe})/Ge (2 nm)]$_{15}$ with the Fe layer thickness of $0.5 \leq d_{Fe} \leq 4$ nm, (iii) [Fe (3 nm)/(Ge/Si/Ge)(d_S)]$_{15}$, and (iv) [Fe (3 nm)/(Si/Ge/Si) (d_S)]$_{15}$ Mls. For series (iii) and (iv), d_S denotes $d_{Ge} + d_{Si} + d_{Ge}$ and $d_{Si} + d_{Ge} + d_{Si}$, respectively. The total spacer thickness, d_S = 1.1 nm, corresponding to strong AF coupling for Fe/Si Mls,

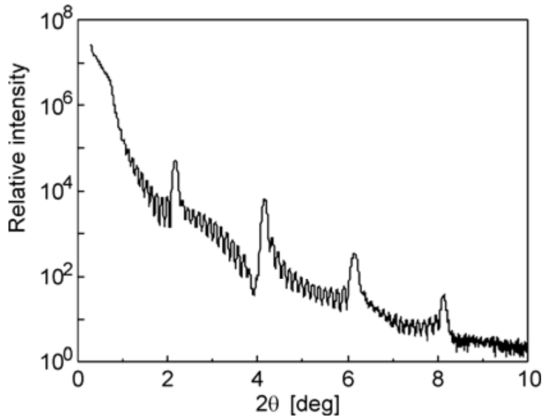

Fig. 1. An example of SAXRD spectrum recorded at room temperature for [Fe(3 nm)/Ge(2 nm)]$_{15}$ Mls

was kept constant and the partial thicknesses of both components were varied. Magnetic and structural properties were investigated at RT by a vibrating sample magnetometer (VSM) and by conversion electron Mössbauer spectroscopy (CEMS), respectively. Well-defined multilayered structures for the investigated Mls were confirmed by small-angle X-ray diffraction (SAXRD), an example spectrum of which is shown in Fig. 1.

3. Results and discussion

The dependence of the saturation field (H_S) on the spacer thickness (d_S), measured at RT for [Fe (3 nm)/Ge (d_{Ge})]$_{15}$ and [Fe (3 nm)/Si (d_{Si})]$_{15}$ Mls is shown in Fig. 2. As can be seen, in contrast to Fe/Si Mls, Fe/Ge reveals no AF coupling in the entire range of examined Ge spacer thicknesses. Figure 3 shows the Fe thickness dependence of magnetic moment per surface area (m/S) for [Fe (d_{Fe})/Ge (2 nm)]$_{15}$ and [Fe (d_{Fe})/Si (2.5 nm)]$_{15}$ Mls (see also [3]). From the interception of the straight line with the d_{Fe} axis we conclude that about 1 nm (0.5 nm at each interface) of sputtered Fe intermixes with Ge and that non-ferromagnetic Fe–Ge structures are formed. As can be seen, this value is twice as large as that found in Fe/Si Mls.

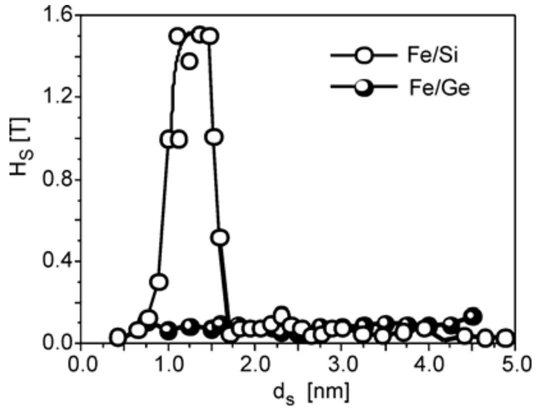

Fig. 2. The saturation field (H_S) of Fe(3 nm)/Si(d_S) and Fe(3 nm)/Ge(d_S) vs. the spacer thickness of Si and Ge, respectively, at room temperature

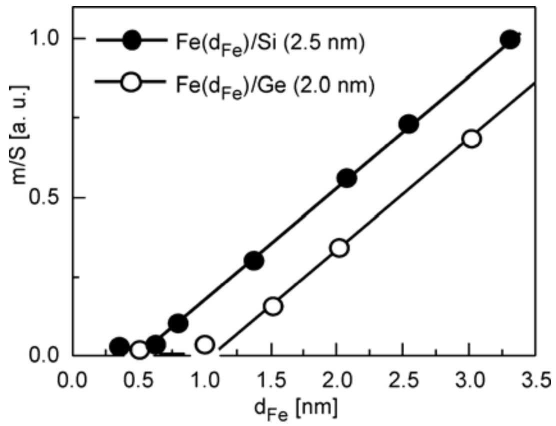

Fig. 3. Magnetic moment per surface area (m/S) at room temperature for Fe(d_{Fe})/Ge (2 nm) and Fe(d_{Fe})/Si (2.5 nm) Mls as a function of Fe thickness

Since, as was already shown, no AF coupling through the Ge spacer occurs, therefore in order to find the influence of Ge on AF coupling in Fe/Si Mls, Fe/(Ge/Si/Ge) and Fe/(Si/Ge/Si) Mls are studied. Magnetic measurements (Fig. 4) reveal that, independently of the position of Ge in the Si spacer, the saturation field decreases with increasing Ge thickness. In the case of the Fe/(Ge/Si/Ge) Mls, due to interdiffussion, the Fe–Ge layer is progressively formed and prevents further diffusion of Fe into the Si layer, which, as we have shown [4, 5], plays a crucial role in the appearance of AF coupling in Fe/Si Mls. For the Fe/(Si/Ge/Si) system, the gradual formation of a continuous Ge layer may occur, leading to the reduction of AF coupling. This process is complete for $d_{Ge} > 0.5$ nm and AF coupling disappears. This reasoning seems to be reflected in the CEMS spectra (Fig. 5).

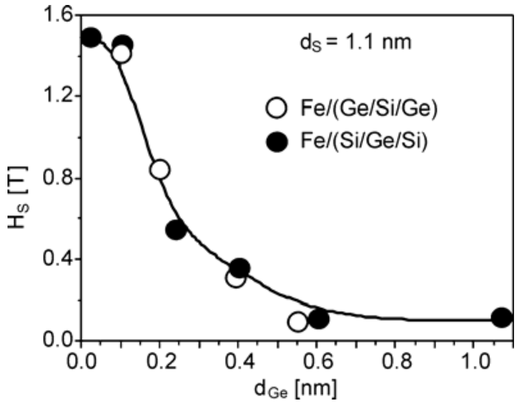

Fig. 4. The influence of Ge sublayer thickness on the value of H_S at room temperature

All the recorded spectra contain two magnetic components:

• The Zeeman sextet with a hyperfine field $H_{hf} \approx 32.8$ T characteristic of the bcc–Fe phase of Fe layers. This value is a little lower than that characteristic of α-Fe, and this reduction can be induced by stress in the Fe layers.

• The magnetic broadened sextet with a hyperfine field $H_{hf} \approx 30$ T and isomer shift δ = 0.05 mm/s, which can be assigned to ferro- or/and antiferromagnetic Fe–Ge phases.

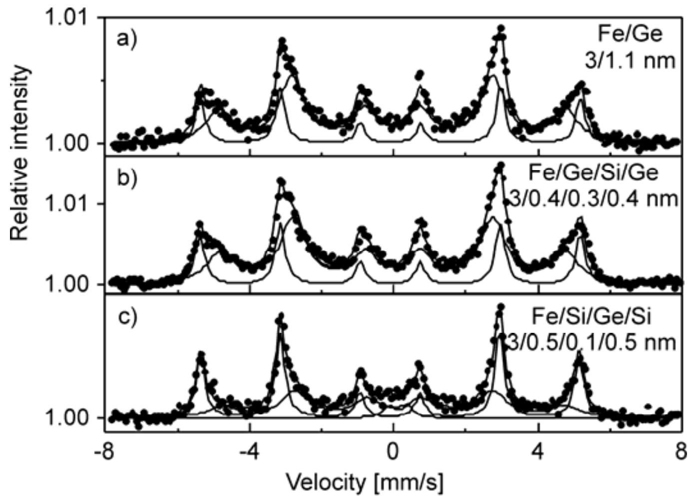

Fig. 5. Room temperature CEMS cpectra for: a) Fe/Ge, b) Fe/(Si/Ge/Si) and c) Fe/(Ge/Si/Ge) Mls. Sublayer thicknesses are indicated

In contrast to Fe/Si Mls [3, 4], however, in Fe/Ge Mls no nonmagnetic quadrupole splitting (QS) doublet is found (Fig. 5a). This may suggest that Fe diffuses into the Ge spacer and only ferromagnetic and/or antiferromagnetic Fe–Ge phases can be formed.

Since all CEMS spectra for Fe/Si Mls contain a pronounced QS doublet due to the appearance of nonmagnetic Fe silicides at Fe/Si interfaces [3, 4], we expect that the introduction of Ge between Fe and Si will prevent the formation of paramagnetic Fe–Si phases, which can be responsible for the observed AF coupling in this system. Indeed, as can be seen from Fig. 5b, for Fe/(Ge/Si/Ge) Mls, a diffusive Fe/Ge interface gives rise to a broadened sextet and no QS doublets are observed. Since all existing Fe–Ge phases are ferro- and antiferromagnetic [6], they are represented by sextets. Our CEMS investigations, however, cannot determine which phases are present in the spacer, and cannot distinguish between ferro- and antiferromagnetic structures. Therefore, the absence of the paramagnetic doublet in Fe/Ge and Fe/(Ge/Si/Ge) suggests that 0.5 nm of Fe diffuses into Ge (Fig. 3) and forms an antiferromagnetic interfacial layer. Thus antiferromagnetic structures similar to FeGe and $FeGe_2$ phases may be formed. In the case of Fe/(Si/Ge/Si) Mls (Fig. 5c), however, both ferro- and paramagnetic structures are present at Fe/Si interfaces. They are represented by a broadened sextet and paramagnetic QS doublet.

4. Conclusions

The absence of AF coupling in Fe/Ge Mls is established. It was shown that during multilayer deposition 0.5 nm of Fe intermixes with Ge and antiferromagnetic structures are formed. Independently of Ge position in the Si spacer, the progressive substitution of Si by Ge leads to a gradual reduction of AF coupling. In Fe/(Si/Ge/Si) Mls, the formation of a continuous Ge layer is responsible for the absence of AF coupling, whereas in Fe/(Ge/Si/Ge) Mls the formation of antiferromagnetic and/or ferromagnetic Fe-Ge structures disables further diffusion of Fe into the Si layer.

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