Influence of Si substrate and interface quality on exchange interactions in ultrathin Fe/NM/Tb film structure

Ye.A.Pogoryelov, V.M.Adeev, V.I.Bondar***

Institute for Magnetism, National Academy of Sciences of Ukraine, 36-B Vernadsky Ave., 03142 Kyiv, Ukraine
*I.Frantsevich Institute for Problems of Materials Science, National Academy of Sciences of Ukraine, 3 Krzhyzhanovsky St., 03142 Kyiv, Ukraine
**G.Kurdyumov Institute for Metal Physics, National Academy of Sciences of Ukraine, 36 Vernadsky Ave., 03142 Kyiv, Ukraine

Trilayer Fe(8 Å)/NM/Tb(12 Å) (NM = Au, Cu) film structures prepared on Si substrates by electron-beam evaporation in an ultrahigh vacuum system with background pressure of $\approx 10^{-9}$ Torr have been studied. The film structure was characterized by X-ray diffraction (XRD) and Auger electron spectroscopy (AES). Magnetic properties of the films were studied using the conventional polar magnetooptic Kerr effect (PMOKE). XRD studies revealed that a Fe silicide with the structure close to Fe_3Si is formed at Si/Fe interface. PMOKE measurements showed that formation of Fe-silicide results in disappearance of short-period oscillations of exchange coupling between Fe and Tb layers. To suppress silicide formation Au (3 Å) or Cu (10 Å) buffer layers were preliminary deposited onto Si substrates. This resulted in clearly visible reappearance of short-period oscillations. But according to AES data these buffer layer thicknesses were nevertheless insufficient to completely prevent interaction between Fe and Si at the interface.

Исследованы трехслойные пленочные структуры Fe (8 Å)/NM/Tb(12 Å) (NM = Au, Cu) на кремниевой подложке, изготовленные методом электронно-лучевого напыления в сверхвысоковакуумной системе при давлении остаточных газов $\approx 10^{-9}$ Тор. Структуру образцов исследовали методами рентгеновской дифрактометрии и Оже-спектроскопии. Магнитные свойства пленок исследовали с помощью традиционного полярного магнитооптического эффекта Керра. Рентгеновские исследования показали, что на поверхности раздела Si/Fe образуется силицид железа, близкий по структуре к Fe_3Si. Согласно данным магнитооптических исследований, образование Fe-силицида приводит к исчезновению короткопериоди-че-ских осцилляций обменного взаимодействия между слоями Fe и Tb. Для предотвращения образования силицида на подложки предварительно наносили буферный слой Au (3 Å) или Cu (10 Å). Это привело к появлению короткопериодических осцилляций. Однако, согласно данным Оже-спектроскопии, такая толщина буферных слоев все еще недостаточна для полного предотвращения взаимодействия кремния и железа.

To develop new multilayered ultrathin film structures for modern fields of microelectronics, new approaches are required. Due to existence of exchange coupling between magnetic layers separated by a nonmagnetic spacer, it is possible to obtain materials with new unique magnetic properties. These could be achieved when rare earth metals having a large magnetic moment per atom are used as one of the magnetic layers. The previous studies of Fe/Au/Tb structures prepared by molecular-beam epitaxy [1] have shown that when different types of substrates (Si or quartz) are used, the amplitude of exchange coupling oscillations varies significantly. For struc-

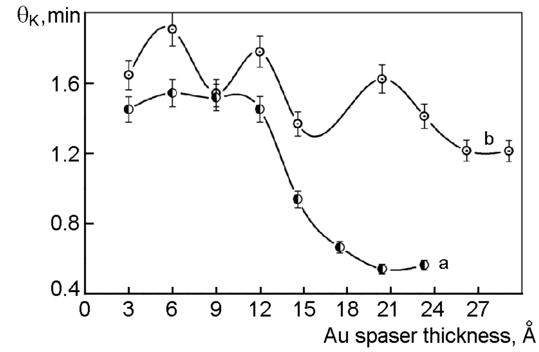

Fig. 1. PMOKE data for Fe/Au/Tb film structures without (a) and with (b) Au interlayer at the Si/Fe interface.

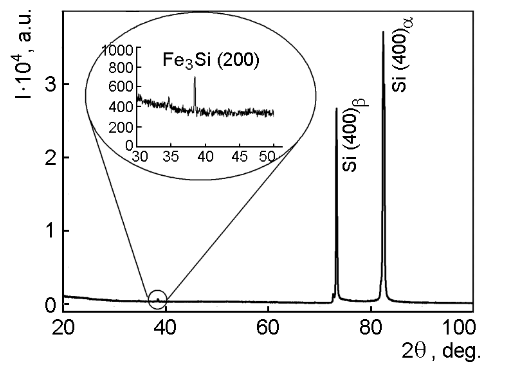

Fig. 2. XRD studies of Si/Fe interface showing the existence of Fe silicide.

tures on Si substrate, the amplitude of obtained dependences was found to be almost one decimal order smaller than the one for quartz substrate. It is known that when Fe is deposited on Si, a Fe-silicide of significantly reduced magnetization may arise at the Si/Fe interface [2]. Thus, taking into account that the film is ultrathin, it becomes necessary to consider the substrate influence on the behavior of exchange interactions in the structures under investigation.

In this work, the exchange coupling in ultrathin Fe(8 Å)/NM/Tb(12 Å) film structures was studied (NM = Au, Cu). The film samples were prepared on Si substrates by electron-beam evaporation in an ultrahigh vacuum system keeping a background pressure of about 10^{-9} Torr. The deposition rates were in the range of 0.1 to 0.4 Å/s and were controlled by a quartz microbalance. In order to evaluate the influence of the substrate on exchange processes in such structures, two identical series of trilayer film samples were prepared. One of the series contained an ultrathin NM buffer layer deposited directly on Si substrate. To find out whether iron-silicide is formed on Si/Fe interface in the investigated film structures, those were studied by X-ray diffraction (XRD) in Co K_α radiation ($\lambda = 1.79021$ Å). The film structure was also analyzed by Auger electron spectroscopy (AES). Magnetic properties of films were investigated using the polar magnetooptic Kerr effect (PMOKE).

XRD patterns of a single 8 Å iron film on Si substrate are presented in Fig. 1. In XRD pattern, two peaks $(400)_\alpha$ and $(400)_\beta$ are clearly seen corresponding to Si (100) with the lattice constant $a = 5.4307$ Å. These signals are related to the substrate. A weak reflex at 38°29′ corresponds to the lattice constant $a = 5.44$ Å. The most close to these parameters is the Fe-silicide $Fe_3Si(200)$ with the lattice constant $a = 5.6$ Å. Thus, the results obtained confirm directly the formation of Fe silicide at the Si/Fe interface. That is to say, the iron in the investigated film structures exists mainly not in pure form, but as a Fe-silicide.

Results of PMOKE studies for two series of Fe/Au/Tb films with and without Au buffer layer are presented in Fig. 2. It is seen that the presence of Au buffer layer on Si substrate results in significant changes into oscillating behavior of Kerr angle (θ_K) as a function of the Au spacer thickness. Curve (a) corresponds to Fe/Au/Tb trilayers deposited directly on Si. At first sight, it may seem that there are no oscillations at all, but only a sharp decrease of θ_K value at certain spacer thickness. But if we assume that the distance between the maximum (at about 7 Å of spacer thickness) and the minimum (at 20.4 Å) corresponds to the half-period of oscillating dependence, then it is possible to calculate the period value. The calculation gives us the value of 8.9 monolayers of Au spacer (ML_{Au}) which is very close to the long-period value 8.6 ML_{Au}, known from theoretical and experimental studies [3, 4]. This period value is also equal to the long period of oscillations determined from anomalous Hall measurements for the same structures prepared by molecular-beam epitaxy on quartz substrates [1]. A quite different picture is observed when 1 ML_{Au} is introduced into Si/Fe interface. Dependence of θ_K on the Au spacer thickness is presented by curve (b). Here, short-period oscillations at θ_K about 2.41 ML_{Au} are clearly seen.

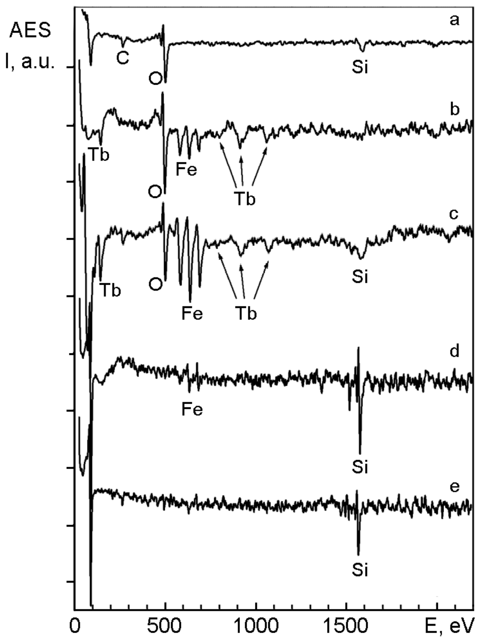

Fig. 3. AES spectra of Fe/Au/Tb film structures with Au buffer layer on Si substrate.

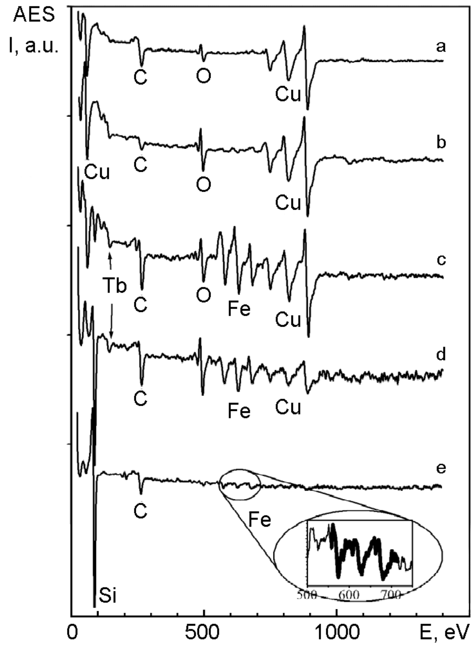

Fig. 4. AES spectra of Fe/Cu/Tb film structures with Cu buffer layer on Si substrate.

In general, the short-period oscillations are highly sensitive to inhomogeneities of interfaces between magnetic layers and spacer. Those may disappear if the size of such inhomogeneity becomes comparable with the period value or exceeds it [3, 5]. So we can conclude that in the case of iron-silicide formation, the interface between iron layer and spacer becomes very inhomogeneous.

The iron silicide formation was confirmed also indirectly by AES studies (Fig. 3). It was shown that oxygen is present over the whole depth of the Fe/Au/Tb structure (Fig. 3(a–c)), possibly due to oxidation in air. When approaching the substrate, the oxygen signal disappears, indicating complete removal of metallic layers. But nevertheless, the iron signal is still visible in AES spectra (Fig. 3(d)). This can indicate existence of layer being a certain iron-Si compound. But unfortunately, Auger studies were unable to clear up the influence of ultrathin gold buffer layer on the processes of silicide formation, possibly due to insufficient sensitivity of the method and also to coincidence of Au signal with the low-energy signal for Tb.

The buffer layer influence was clarified when a copper layer was used. Fig. 4 presents the results of AES studies of trilayer Fe/Cu/Tb film structure with copper buffer layer are presented. Copper signal is clearly observable. It is interesting that, in spite of existence of 10 Å copper buffer layer, it is impossible to protect completely iron layer against interaction with Si substrate. As is seen from AES spectra at the final stages of film structure etching (Fig. 4(e)) when the copper buffer layer is removed, iron peaks are still present. According to the last literature data [6–8], in order to suppress completely the silicide formation, it is necessary to cover Si substrate with at least 8 or 9 monolayers of copper.

In conclusion, it has been shown that when iron film is deposited directly on Si substrate, an iron silicide close to Fe_3Si is formed. The iron silicide formation causes suppression of short-period oscillations of exchange coupling. Introduction of ultrathin NM buffer layer into Si/Fe interface suppresses formation of Fe silicide that results in significant change of exchange coupling character between Fe and Tb layers. This is manifested by appearance of short-period oscillations of θ_K for film samples with the buffer layer. Buffer layer thickness values used in investigated film structures are nevertheless insufficient for complete suppression of iron-silicide formation.

References

1. E.Shypil, A.Pogorilyy, Ye.Pogoryelov et al., *J.Magn.Magn.Mater.*, **242–245**, 532 (2002).
2. F.Zavaliche, W.Wulfhekel, H.Xu, J.Kirschner, *J.Appl.Phys.*, **88**, 5289 (2000).

3. P.Bruno, C.Chappert, *Phys. Rev. Lett.*, **67**, 1602 (1991).
4. J.Unguris, R.J.Celotta, D.T.Pierce, *Phys. Rev. Lett.*, **79**, 2734 (1997).
5. P.M.Levy, S.Maekawa, P.Bruno, *Phys. Rev. B*, **58**, 5588 (1998).
6. Z.H.Zhang, S.Hazegawa, S.Ino, *Surf. Sci.*, **415**, 363 (1998).
7. P.Castrucci, R.Gunnella, R.Bernardini et al., *Surf. Sci.*, **476**, 43 (2001).
8. K.Pedersen, T.B.Kristensen, T.G.Pederser et al., *Phys. Rev. B*, **66**, 153406 (2002).

Вплив Si підкладки та якості поверхні розділу на обмінні взаємодії в ультратонких структурах Fe/NM/Tb

Є.А.Погорєлов, В.М.Адєєв, В.І.Бондар

Досліджено тришарові плівкові структури Fe (8 Å)/NM/Tb(12 Å) (NM = Au, Cu), виготовлені на кремнієвій підкладці методом електронно-променевого напилювання в надвисоковакуумній системі при тиску залишкових газів $\approx 10^{-9}$ Тор. Структуру зразків досліджували методами рентгенівської дифрактометрії та Оже-спектроскопії. Магнітні властивості плівок досліджували за допомогою традиційного полярного магнітооптичного ефекту Керра. Рентгенівські дослідження показали, що на поверхні розділу Si/Fe утворюється силіцид заліза, близький за структурою до Fe_3Si. Згідно з даними магнітооптичних досліджень, утворення Fe-силіциду призводить до зникнення короткоперіодичних осциляцій обмінної взаємодії між шарами Fe та Tb. Для запобігання утворенню силіциду на підкладки попередньо наносили буферний шар Au (3 Å) або Cu (10 Å). Це призвело до появи короткоперіодичних осциляцій. Проте, згідно даних Оже-спектроскопії, такої товщини буферних шарів все ще недостатньо для повного запобігання взаємодії кремнію та заліза.