 

# Exchange coupling peculiarities in ultrathin Fe/Cu/Tb film structures on Si substrates

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Exchange coupling in ultrathin Fe(8 Å)/$x$Cu/Tb (12 Å) film structure has been studied. The film samples were prepared on Si substrates by electron-beam evaporation in an ultrahigh vacuum system having a background pressure of $\approx 10^{-9}$ Torr. To suppress formation of Fe-silicide on Si/Fe interface, a buffer Cu layer (10 Å) was preliminary deposited onto Si substrate. To characterize the film, ferromagnetic resonance (FMR) and a know-how based on the Hall-like effect in zero external magnetic field were used. It has been shown that when Cu spacer thickness is increased, a periodical change of Fe film resonance field occurs. Application of FMR allowed to conclude directly the sign of exchange coupling between Fe and Tb layers or, in other words, the mutual orientation of their magnetizations. These results were also confirmed by new technique based on Hall-like effect. The period of oscillations obtained has been measured to be of about 2.65 Cu monolayers and is in good agreement with the value of 2.6 monolayers for the Cu(001) Fermi surface.

Исследовано обменное взаимодействие в ультратонкой пленочной системе Fe(8 Å)/$x$Cu/Tb(12 Å). Пленочные образцы получали методом электронно-лучевого напыления на кремниевую подложку в сверхвысоковакуумной системе с давлением остаточных газов $\approx 10^{-9}$ тор. Для предотвращения образования на поверхности раздела Si/Fe силицида железа использовали буферный слой Cu толщиной 10 Å, предварительно нанесенный на кремниевую подложку. Для характеризации пленочных структур использовали ферромагнитный резонанс (ФМР), а также ноу-хау на основе Холл-подобного эффекта в нулевом внешнем магнитном поле. Показано, что с изменением толщины прослойки меди происходит периодическое изменение резонансного поля железа. Использование ФМР позволило напрямую судить о знаке обменного взаимодействия между слоями железа и тербия, или другими словами, о взаимной ориентации их намагниченностей. Эти результаты также подтверждены методикой на основе Холл-подобного эффекта. Период полученных осцилляций обменного взаимодействия составил $\approx$2.65 монослоев меди и находится в хорошем соответствии с периодом 2.6 монослоуи для поверхности Ферми Cu(001).

Elaboration of new multilayered ultrathin film structures for modern fields of microelectronics demands new approaches. Due to existence of exchange coupling between magnetic layers separated by nonmagnetic spacer, it is possible to obtain materials with new unique magnetic properties. These could be achieved if we use rare earth metals, which have a large magnetic moment per atom, as one of the magnetic layers. Prior authors have studied the exchange coupling in trilayer Fe/Au/Tb film structures and it was shown that a change of the magnitude and sign of the exchange interactions between Fe and Tb layers occurs as the Au spacer thickness increases [1]. The use of Cu as the spacer material is also of particular interest. On the one hand, Cu has very close physical properties to Au ones, the shape of their Fermi surfaces being almost the same [2]. On the other hand, Cu has some potential advantages: its conductivity is a little larger than that of gold, therefore, more conduction electrons can be involved into exchange processes. Hence, the magnitude of the exchange coupling can be increased. This was proved in the literature, where the exchange coupling was studied between two ferromagnetic layers separated by Au and Cu spacers [3].

In this work, exchange coupling in ultrathin Fe(8 Å)/$x$Cu/Tb(12 Å) film structure was studied. The film samples were prepared on Si substrates by electron-beam evaporation in an ultrahigh vacuum system having a background pressure of $\approx 10^{-9}$ Torr. The deposition rates were in the range of 0.1–0.4 Å/s and were controlled by the quartz microbalance. As it was shown in our previous investigations [4], when a Fe film is deposited directly on Si substrate, Fe silicide is formed. In Fe/Au/Tb structures, this resulted in disappearance of the short-period oscillations of exchange coupling. Deposition of ultrathin Au buffer layer onto Si substrate suppressed Fe-silicide formation, so the short-period oscillations became apparent. That is why when preparing film samples with Cu spacer, Si substrate was covered with 10 Å Cu buffer layer. To characterize the films, ferromagnetic resonance (FMR) providing the information on the magnetization of samples and the character of exchange coupling between magnetic layers, and also a know-how based on the Hall-like effect at zero external magnetic field were used.

According to results of FMR studies of the control 8 Å Fe film, if the buffer layer is used, the resonance field of this film shifts abruptly to about 11.7 mT as compared to that of 120 mT for the same film but deposited directly onto Si substrate. The resonance field for bulk Fe is about 50 mT [5]. Such sharp decrease of the resonance field for the ultrathin Fe film on Cu buffer layer can indicate a sharp increase of its magnetization. It is known that Fe deposited at room temperature grows epitaxially on Cu(100) up to 10–12 monolayers (ML) [6]. A face-centered cubic (fcc) crystal phase with a tetragonal distortion is formed up to 5 or 6 ML. Also it was shown [7] that at 2–4 ML thickness, a bcc-like phase can form along with the fcc phase. Moreover, the films around 3 ML have the highest bcc-like content. At this critical coverage, the fcc layers of the film show a complex magnetic behavior due to the different amounts of lattice expansion along the surface normal [8]. This behavior is associated with changes in electronic properties, in

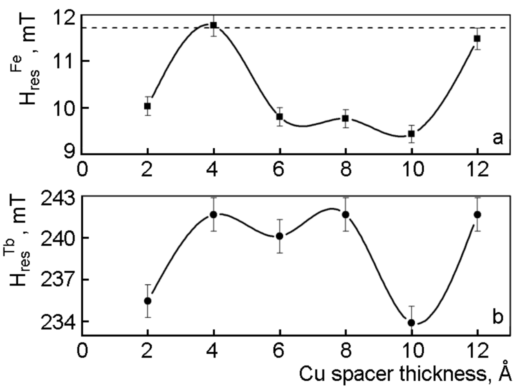


Fig. 1. FMR studies of Fe/Cu/Tb structures. Oscillation of Fe and Tb resonance fields as a function of Cu spacer thickness.

particular, with a splitting of the spin-up and spin-down $d$-states, which is related closely to the unit cell magnetic moment, hence, to the film magnetization. In the case when Fe film of 3 ML thickness is sandwiched between two Cu layers, its magnetization is oriented in its plane.

It was shown that when Cu spacer thickness is increased, the periodical change of Fe film resonance field occurs (Fig.1a). Moreover, FMR allowed to observe the resonance for Tb films (Fig. 1b). The application of FMR makes it possible to conclude the sign of the exchange interactions between Fe and Tb layers. Within the coupled trilayer system, the Fe film resonance field is shifted towards lower field values as compared to that for uncoupled film, indicating the existence of ferromagnetic coupling [9]. Nevertheless, the FMR method is an integral one, so it is difficult to obtain the true magnetization values of each magnetic layer. Besides, during FMR measurements, the film sample is situated in the external magnetic field.

As it was shown in our previous studies of Fe/Au/Tb film structures [4], the exchange coupling between Fe and Tb layers is influenced by external magnetic field. That is why the measurements on Fe/Cu/Tb film structures were carried out using a technique based on the Hall-like effect in zero external magnetic field. Results are presented on Fig. 2. In comparison with the coupling oscillations for the trilayer with Au spacer [4], which appeared to be close to RKKY model, the oscillating dependence for the structure with Cu spacer is more complex. Nevertheless, the period of these oscillations is about 2.63 ML of Cu ($ML_{Cu}$).

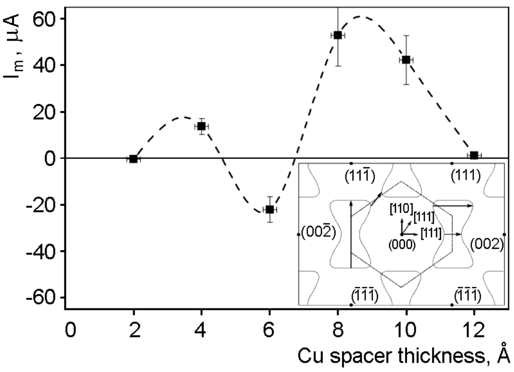


Fig. 2. Oscillating dependence of Hall-like effect in Fe/Cu/Tb film structures. Inset: the cross-section of Cu Fermi surface [12].

This value is close to the short period of 2.56 $ML_{Cu}$ predicted theoretically [10] and to the value of 2.6 $ML_{Cu}$, obtained from the experimental studies of Fe/Cu/Fe structure [11]. This short period value corresponds to the [001] orientation of the Cu spacer lattice (inset in Fig. 2) [12]. There should also be the long period of 5.88 ML Cu, which also corresponds to [001] orientation, but it was not observed on the experiment. Nevertheless, existence of the short-period oscillations indicates the good quality of interfaces between magnetic layers and spacer.

In conclusion, FMR studies of Fe/Cu/Tb structures on Si substrates have shown oscillations of resonance fields for Fe and Tb layers as a function of Cu spacer thickness with the indication of coupling sign change. This was also confirmed by Hall-like effect measurements in zero external magnetic field. Disagreement of the obtained oscillations with the RKKY model may be possible as a result of the influence of Fe film magnetic inhomogeneities on exchange processes, which can be of the same nature as the influence of the external magnetic field.

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# Особливості обмінної взаємодії в ультратонких плівкових структурах Fe/Cu/Tb на кремнієвих підкладках


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Досліджено обмінну взаємодію в ультратонкій плівковій системі Fe(8 Å)/$x$Cu/Tb(12 Å). Плівкові зразки отримували методом електронно-променевого напилювання на кремнієву підкладку в надвисоковакуумній системі із тиском остаточних газів ≈$10^{-9}$ тор. Для запобігання утворенню на поверхні поділу Si/Fe силіциду заліза використовували буферний шар Cu товщиною 10 Å, який попередньо наносили на кремнієву підкладку. Для характеризації плівкових структур використовували феромагнітний резонанс (ФМР), а також ноу-хау на основі Холло-подібного ефекту в нульовому зовнішньому магнітному полі. Показано, що із зміною товщини прошарку міді відбувається періодична зміна резонансного поля заліза. Використання ФМР дозволило судити про знак обмінної взаємодії між шарами заліза та тербію, або іншими словами, про взаємну орієнтацію їх намагніченостей. Ці результати також підтверджено методикою на основі Холло-подібного ефекту. Отримане значення періоду осциляцій обмінної взаємодії складає ≈2.65 моношарів міді і добре узгоджується з періодом 2.6 моношарів для поверхні Фермі Cu(001).