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Influence of the interface morphology on the exchange coupling in Fe/Pd/Fe(0 0 1) structures

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Abstract

Previous studies of Fe/Pd/Fe trilayers revealed the presence of oscillatory behavior in exchange coupling superimposed on a ferromagnetic background. These structures were characterized by small size terraces (5 nm on a side) at the first Fe/Pd interface. A number of theoretical and experimental studies have shown that the exchange coupling depends on interface quality. However, systematic studies of this issue have been limited. To study the influence of the interface morphology on exchange coupling we have recently grown a series of Fe/Pd/Fe trilayers on Fe whisker substrates and on GaAs substrates by MBE. These structures exhibit terraces at the first Fe/Pd interface ranging in size from 3 to 1000 nm. We characterized the quality of our structures by RHEED patterns and RHEED intensity oscillations. We used MOKE and BLS techniques to study the strength of the exchange coupling. Whereas previous studies found ferromagnetic coupling for Pd interlayers with thicknesses on the order of six monolayers, we find significant antiferromagnetic coupling in the samples with smooth interfaces. In contrast, the samples with rougher interfaces show weak ferromagnetic coupling or no coupling. © 1999 Elsevier Science B.V. All rights reserved.

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The experimental and theoretical studies of exchange coupling in Fe/Pd structures have attracted wide attention for a long time [1], since palladium properties are intriguing. For example, the exchange coupling in Fe/Pd/Fe trilayers, grown on Ag(0 0 1) single crystal substrates at room temperature, has been studied by Celinski et al. [2,3]. These authors observed that the exchange coupling was strongly temperature dependent for Pd films less than 8 monolayers (ML) thick. For Pd films thicker than 9 ML the exchange coupling was weak with minimal temperature dependence, if any. The thickness dependence of the exchange coupling in Fe/Pd/Fe structures was not trivial; with increasing Pd thickness an oscillatory behavior was superimposed on the monotonically decreasing ferromagnetic background. The period of oscillation was ~4 ML. For Pd interlayers thicker than 12 ML, the exchange coupling became antiferromagnetic. Studies [4,5] of the exchange coupling in Fe/Pd(0 0 1) superlattices and Fe/Pd/Fe(0 0 1) trilayers grown on MgO substrates revealed only ferromagnetic coupling, indicating a strong dependence of exchange coupling on growth conditions and surface morphology.

Recent theoretical calculations [6,7] of the exchange coupling for the Fe/Pd/Fe(0 0 1) structures predicted that the exchange coupling should exhibit oscillatory behavior with antiferromagnetic coupling for very thin (1, 2, and 6 ML thick) Pd interlayers. Such a theoretical prediction is in contradiction to the behavior in Fe/Pd/Fe trilayers described above. It is an aim of our present work therefore to study the influence of the interface morphology on exchange coupling for Pd interlayers with thicknesses on the order of six monolayers.

We prepared a series of Fe/Pd structures using molecular beam epitaxy with pressure in 10^{-10} Torr range.

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To modify the morphology at first Fe/Pd interface we used two types of substrates, Fe whiskers and GaAs(0 0 1). Well prepared Fe(0 0 1) whiskers represent the best available metallic template and are characterized by atomic terraces whose dimensions are in excess of 1 μm. We prepared two Fe whiskers using the recipe described in detail by Heinrich et al. [8]. It consisted of a sequence of Ar^+ sputtering and annealing at 970 K. The RHEED pattern for the Fe whiskers exhibited well defined spots. Pd was then grown at 350 K on the Fe whisker surface. We observed the RHEED intensity oscillations indicating that the Pd growth proceeded in a pseudolayer-by-layer mode. We grew 6 ML of Pd on first Fe whisker. On the second Fe whisker we prepared two zones with different roughnesses at the first Fe/Pd interface by growing an additional 4 ML of Fe on part of Fe whisker surface. The characteristic splitting of the specular spot in the RHEED pattern revealed the presence of terraces with average size of 3 nm. 7 ML of Pd was then grown over the entire whisker followed by a thin Fe film grown at ~ 340 K. All samples were capped with a 20 ML epitaxial film of Au prior measurements in ambient condition.

The GaAs substrates were, after initial etching in diluted HF, prepared by a cycle of sputtering and annealing at 820 K. All structures were grown on reconstructed, As depleted surfaces of GaAs(0 0 1). The initial Fe seed layer and then the Ag(0 0 1) template were grown at 370 K and showed a single crystal RHEED pattern. Nevertheless, we annealed the Ag template at 620 K to improve its crystallinity. We grew initially 6 ML of Fe at room temperature, and then we raised the temperature to 420 K to grow 6 additional Fe layers. This allowed us to significantly increase the average terrace size of the Fe film from 3 to 50 nm. We then grew the Pd film using the RHEED intensity oscillations as an indicator of the film thickness. The second layer of Fe, 6 ML thick, was grown on the Pd and the sample was capped with 20 ML of Au.

We studied the magnetic properties using Brillouin light scattering (BLS) and magneto-optical kerr effect (MOKE). All measurements were performed at room temperature. The BLS spectra were taken in the back scattering configuration using 50, 30 and 25 GHz free spectral range. We used an argon ion laser with $\lambda = 514.4$ nm and 45° scattering angle.

Fig. 1 shows the results of the BLS measurements on the Fe whisker/7Pd/7Fe/20Au characterized by two zones with small and large terraces at first Fe/Pd interface. We observe a small difference in the frequencies of the spin wave modes between the regions with different terrace sizes. From the data we determine the strength of the exchange coupling for these two regions. The sample with large terraces exhibited a small ferromagnetic coupling of 0.05 erg/cm^2, while small terrace sizes resulted in zero coupling.

Fig. 2 shows the result of the BLS measurements on the Fe whisker/6Pd/6Fe/20Au structures. We observed

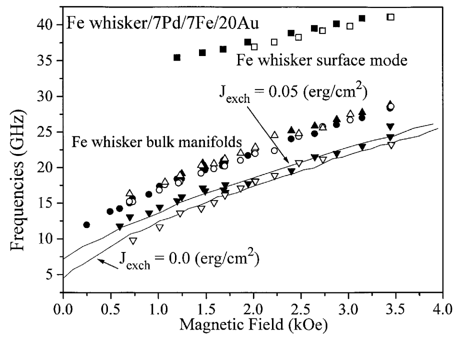

Fig. 1. BLS results (frequency vs. magnetic field) for Fe whisker/7 Pd/7 Fe sample. Open symbols represent results from the small terrace region, while closed symbols represent the large terrace region.

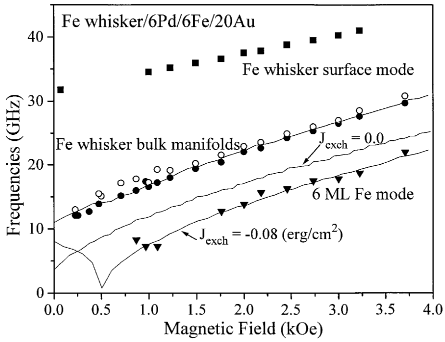

Fig. 2. BLS results for the Fe whisker/6 Pd/6 Fe sample. The lower frequencies, compared to Fig. 1, result from antiferromagnetic coupling.

a significant down-shift of mode frequencies of the 6 ML Fe film indicating the presence of antiferromagnetic coupling in our structure. Since we were unable to measure the BLS spectra at low fields we can only determine the overall strength of the antiferromagnetic coupling in saturation, that is $J_{exch} = J_1 - 2J_2$, where J_1 and J_2 are the strengths of the bilinear and biquadratic exchange coupling, respectively. The result of our fitting indicates that the $J_{exch} = -0.08$ erg/cm^2.

We performed MOKE measurements on 12Fe/xPd/6Fe/20Au structures grown on GaAs substrates. Fig. 3 shows our measurements for $x = \sim 5.5$ ML along easy axis. This sample clearly shows antiferromagnetic coupling. We observed antiferromagnetic coupling also for $x = 5$ ML, though not so strong, while for $x = 6$ and $x = 7.5$ we observed rectangular hysteresis loops indicating ferromagnetic coupling. This conclusion was further confirmed by BLS measurements. For $x = 5.5$, we found $J_1 = -0.095$ erg/cm^2 and $J_2 = 0.012$ erg/cm^2. The solid line and open symbols on Fig. 3 represent our fit and data, respectively. For $x = 5$ ML the antiferromagnetic

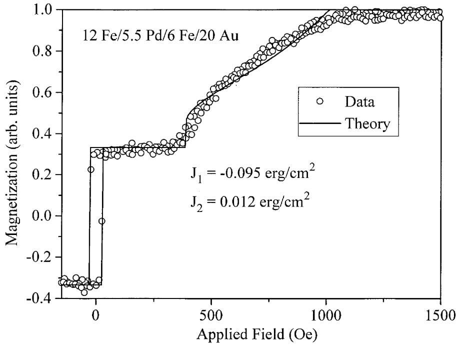

Fig. 3. Hysteresis loop of the 12 Fe/5.5 Pd/6 Fe sample along easy axis.

coupling was significantly weaker with the $J_1 = -0.035$ erg/cm^2 and the $J_2 = 0.01$ erg/cm^2. Note that both samples ($x = 5$ and 5.5 ML of Pd) had the same terrace sizes (~ 50 nm) at first Fe/Pd interface and as a result the observed biquadratic coupling shows similar value indicating that biquadratic coupling is caused by the mechanism proposed by Slonczewski [9].

In conclusion, we observed the antiferromagnetic coupling in Fe/Pd structures for Pd thicknesses of the order of six monolayers. This result is in agreement with theoretical predictions by Stoeffler et al. [6,7]. The strength of the coupling strongly depends on interface morphology. The short terraces (~ 3 nm on side) tend to average out the exchange coupling in Fe/Pd structures. The previously reported [2,3] oscillatory behavior in the strength of the exchange coupling on a ferromagnetic background for Pd interlayers thiner than 12 ML is a consequence of such short terrace sizes at the Fe/Pd interfaces. The largest terraces revealed the antiferromagnetic coupling with the presence of biquadratic coupling introduced by the larger terraces.

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