Semiconductor Physics, Quantum Electronics & Optoelectronics. 2002. V. 5, N 2. P. 212-216.

PACS: 75.70.Ak, 75.70.Cn, 78.20.Ls

Polar magneto-optical Kerr effect studies of interlayer exchange coupling in Fe/Tb bilayers and Fe/Au/Tb trilayers

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Abstract. Interlayer exchange coupling was studied. The investigations were carried out on bilayer (Fe/Tb) and trilayer (Fe/Au/Tb) ultrathin film structures. The films on silica substrate were prepared by electron-beam evaporation in an MBE system with a background pressure of $(1 \div 5) \cdot 10^{-10}$ Torr and maintaining a pressure of $(1 \div 3) \cdot 10^{-9}$ Torr during the film growth. To investigate these film structures polar magneto-optical Kerr effect was used. In bilayers the perpendicular magnetic anisotropy was observed. When a monolayer of Au was interposed at the interface, was observed to disappear. This is because of breaking the short-range interaction between Fe and Tb layers. Instead a long-range indirect exchange via nonmagnetic Au interlayer appears. The increase of Au interlayer thickness ($3 \div 35$ Å) resulted in the oscillations of the Kerr angle. Analogous oscillations are distinctive to the RKKY model of interlayer exchange coupling.

Keywords: polar Kerr effect, exchange interaction, single interface, interfacial spacer, exchange coupling oscillations.

Paper received 14.03.02; revised manuscript received 29.05.02; accepted for publication 25.06.02.

1. Introduction

Coupling between ferromagnetic metal layers, separated by non-magnetic metal interlayers first reported by Grunberg *et al.* [1] in Fe/Cr multilayers has been observed already in many systems: Fe/Al [2], Fe/Ag [3], Fe/Au [2, 4-7], Fe/Pd [8], Fe/Cu [8, 9]. Indirect exchange coupling between ferromagnetic (Fe) layer and rare earth metal (Tb) separated by non-magnetic metal interlayers (Cu, Au, Pt, Ta) was also found [10]. Authors concluded that perpendicular magnetic anisotripy (PMA) in Fe/Tb multilayers is caused by a short range interaction between the nearest neighbors (Fe-Tb) at the interface. A long range indirect exchange via a non-magnetic metal interlayer was also observed. An attempt to find the answers to some questions that were put in this first work on Fe/M/Tb structures [10], where M is non-magnetic metal, was made in [11].

It is important to note that magnetic properties of amorphous Rare Earth – Transition Metal alloy films and multilayers have been studied extensively in the past [12-25]. Among them Fe-Tb system that shows significant PMA, and already find application as magneto-optic data storage media, have been investigated more. Tb/Fe multilayers show better promise for this purpose compared with alloy films, and their magnetic properties have been also well investigated [17-25]. Antiferromagnetic coupling of Fe and Tb magnetic moments at the interface has been established [16, 26] similar to antiferromagnetic interactions in amorphous alloys. However, so far, most of the studies, reported on Fe/Tb, have been done on multilayers.

The present work was undertaken to study the interlayer interactions in a single Fe/Tb bilayers by carefully preparing samples under the cleanest condition. Also the behavior of interlayer coupling between Fe and Tb layers when one and more Au monolayers are introduced at the interface was investigated.

2. Experiment

Two sets of samples, Fe/Tb bilayers and Fe/Au/Tb trilayers on silica substrate were prepared by electron-beam evaporation in an MBE system with a background pressure of 1–5 x 10^{-10} Torr and maintaining a pressure of 1–3 x 10^{-9} Torr during the film growth. To mini-

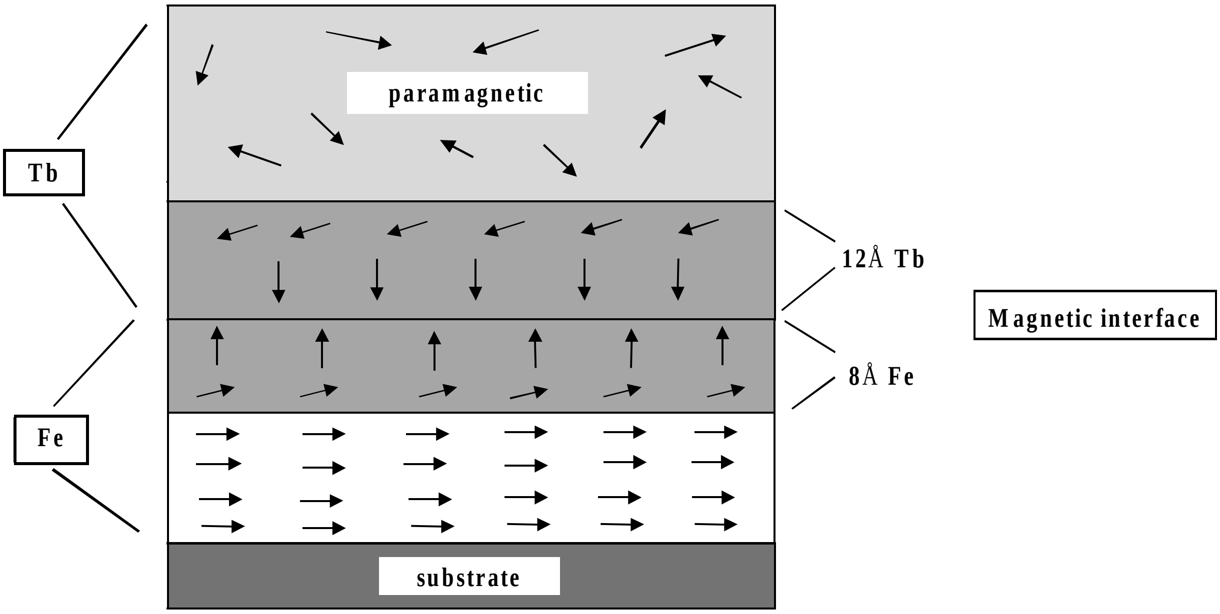

Fig. 1. The model of interlayer coupling at Fe/Tb interface

mize interdiffusion of layers the substrate temperature during evaporation was kept no higher than 0° C. The rates of evaporation did not exceed 0.4 Å/sec and were independently controlled with silica crystal monitors. All the samples were protected with 100 Å thick layer of Al_2O_3.

PMOKE was measured at room temperature using a 630 nm laser in an applied field up to 1.8 T perpendicular to the film plane.

The thicknesses of the individual layers, d_{Fe} and d_{Tb}, were chosen using results of the previous experiments [28-30] and literature data [10], where the ferrimagnetic ordering of Fe/Tb multilayer has been shown. This is caused by the interface properties, where ferromagnetic Fe and paramagnetic Tb being in contact, result in some magnetic moment to be induced in the Tb layer. The coupling is not restricted to the first Tb monolayer (ML). It was described by 'magnetic interface' of the finite volume, spread into both layers close to interface, where Fe - and Tb-atoms are antiparallel coupled showing PMA (Fig. 1). The ratio of MLs, N_{Tb}/N_{Fe}, participating in the completed 'magnetic interface' is usually in the range of 1 to 2, where N_{Tb} and N_{Fe} are the number of corresponding MLs, involved in the coupling. In this range, anisotropy energy is constant and has an approximate value $k_\perp \cong 5 \cdot 10^6$ erg/cm^3 [30]. It was also shown that the radius of pair interaction in this system is 7 – 15 Å [28, 30]. Hence it follows that magnetic interactions in Fe/Tb interfaces begin when each of the layers, d_{Fe} and d_{Tb}, reaches 3 MLs.

Accounting that atomic radii are R_{Fe} = 1.27 Å and R_{Tb} = 1.78 Å, we choose d_{Fe} = 8 Å and d_{Tb} = 12 Å to obtain 3 MLs of Fe and 3 MLs of Tb.

3. Results and discussion

It has been shown that when thin Fe and Tb films are layered one at another, a small magnetic moment is induced in thin Tb film by Ruderman-Kittel-Kasuda-Yosida (RKKY) interaction [10, 27]. Moreover, antiferromagnetic coupling of Tb and Fe magnetic moments at the interface has also been established [16, 26] similar to antiferromagnetic interactions in amorphous alloys. Hence, three kinds of interactions are to be discussed in Fe/Tb interfaces: i) between Fe-Tb atoms with antiparallel orientation, which gives the main contribution to PMA. RKKY interaction is evaluated for this case as $D_{Fe\text{-}Tb} = -2.152 \cdot 10^{-14}$ erg/cm^3; where D is a constant of interaction [31], ii) ferromagnetic interaction between Fe-Fe atoms, that is one order of magnitude smaller, $D_{Fe\text{-}Fe} = -4.805 \cdot 10^{-15}$ erg/cm^3; iii) interaction between Tb atoms, which are magnetized at the interface, that is also ferromagnetic, $D_{Tb\text{-}Tb} = 3.47 \cdot 10^{-16}$ erg/cm^3. Interaction between Fe-Fe atoms gives magnetization component in plane of film, while Fe-Tb interaction results in perpendicular magnetization component (Fig. 1). In bare outlines this model was first discussed by Yamauchi *et al.* [26], where they described four regions in magnetic structure of artificially layered Tb-Fe films: ferrimagnetically coupled Tb-Fe, ferromagnetic Fe, ferromagnetic Tb and magnetically compensated Tb regions. Later this magnetic structure was improved by Shan and Sellmyer [16], who emphasized that nanoscale layer thickness should be used to show large PMA. Hoffmann and Scherschlicht confirmed this simple model of multilayer system: ferromagnetic Fe (in plane anisotropy) / ferrimagnetic Fe / Tb (perpendicular anisotropy) / paramagnetic Tb / ferrimagnetic Fe / Tb

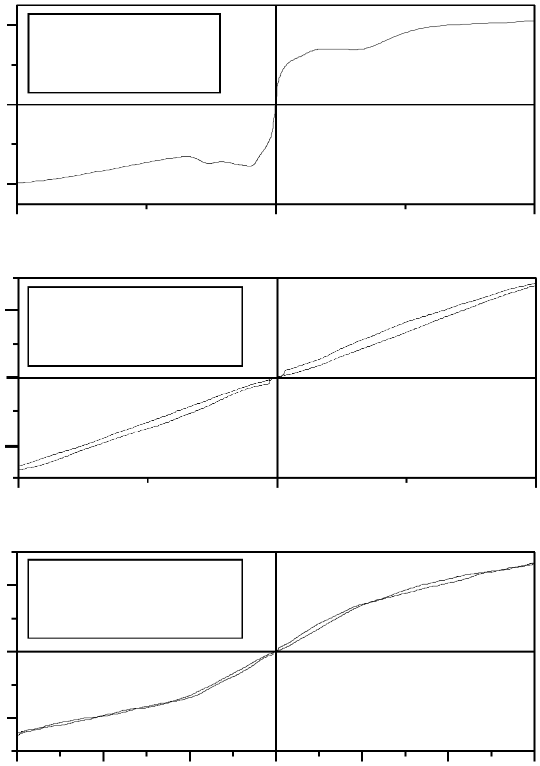

Fig. 2. PMOKE loops for Fe/Tb bilayers (a) and Fe/Au/Tb trilayers (b and c).

(perpendicular anisotropy) / ... [10]. In Fig. 1 we show the detailed magnetic structure of one interface. One can see that if to choose d_{Fe} and d_{Tb} to be equal to "magnetic interface", the in-plane component will tend to minimum.

According to PMOKE data for Fe/Tb bilayers (Fig. 2a) the perpendicular magnetization component was always observed at low fields, usually up to 100 mT. This follows from perpendicular geometry, which is used in PMOKE method.

To further understand the extent of coupling in Fe-Tb system, we introduced one ML of Au at the interface. As one can see from the PMOKE data for trilayers (Fig. 2b) the introduction of Au spacer at the interface causes the disappearance of the perpendicular magnetization component. It means that only one Au ML interposed between Fe and Tb layers was sufficient to shield the short-range magnetic interactions, which resulted in PMA. It is natural to suppose that all the magnetic moments in such trilayers are already in the film plane. Though the same PMOKE data for the trilayers (Fig. 2c) show that some small loop of magnetization with jog at higher fields (500–600 mT) is still present. It means that the angle between Fe and Tb magnetic moments is not zero. Fe and Tb layers still interact via monolayer of Au.

So, one ML of Au at the Fe-Tb interface thus dramatically effects the magnetic interactions, entirely eliminating the short-range exchange between Fe and Tb atoms. Instead, a long-range indirect exchange interaction via non-magnetic Au interlayer is observed, leading to the increase in the total magnetic moment. Pan *et al.* [32] have reported that a magnetic moment is induced in Au by Fe to describe the enhancement of Fe magnetic moment in FeAu alloy film, prepared by alternate monatomic deposition. Hoffman also observed that the net magnetic moment for Fe/Au/Tb/Au multilayers is larger than that of pure Fe layers [10]. Magnetic moment induced in Tb still exists. Its orientation as to Fe-moment is a point of future study.

With further increase of Au spacer thickness the oscillations of the PMOKE angle are observed (see Fig. 3b). These oscillations are interpreted as the oscillations of the indirect exchange coupling between Fe and Tb layers via Au spacer. Comparing these data with the data obtained by Hoffmann [10] (Fig. 3a) for Fe/Au/Tb multilayers we can see quite good correlation. The oscillations of Kerr angle are also supported by the data obtained by the anomalous Hall effect measurements (Fig. 4) [33].

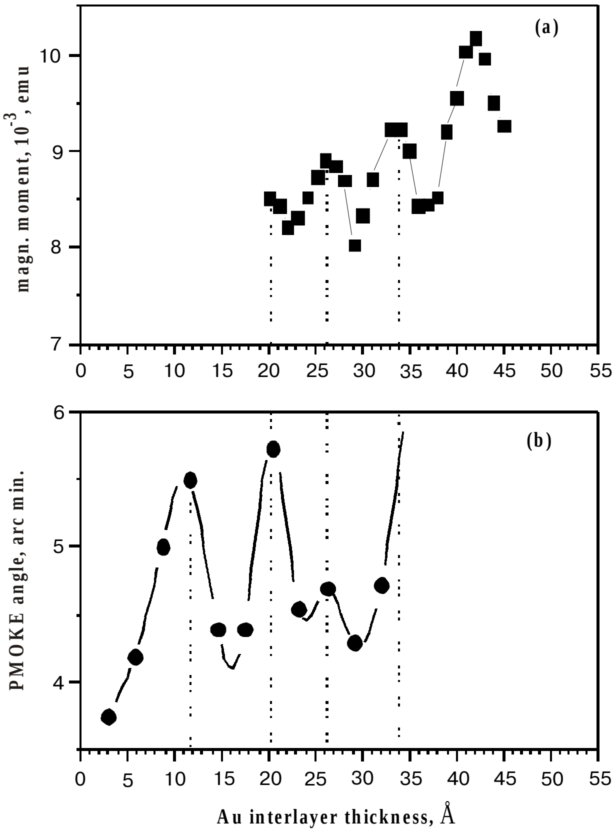

Fig. 3. Oscillation of the net magnetic moment observed for a) (Fe/x Au/Tb/x Au)$_{12}$ multilayers in [10] and for b) Fe/x Au/Tb trilayers (this work) as a function of Au interlayer thickness.

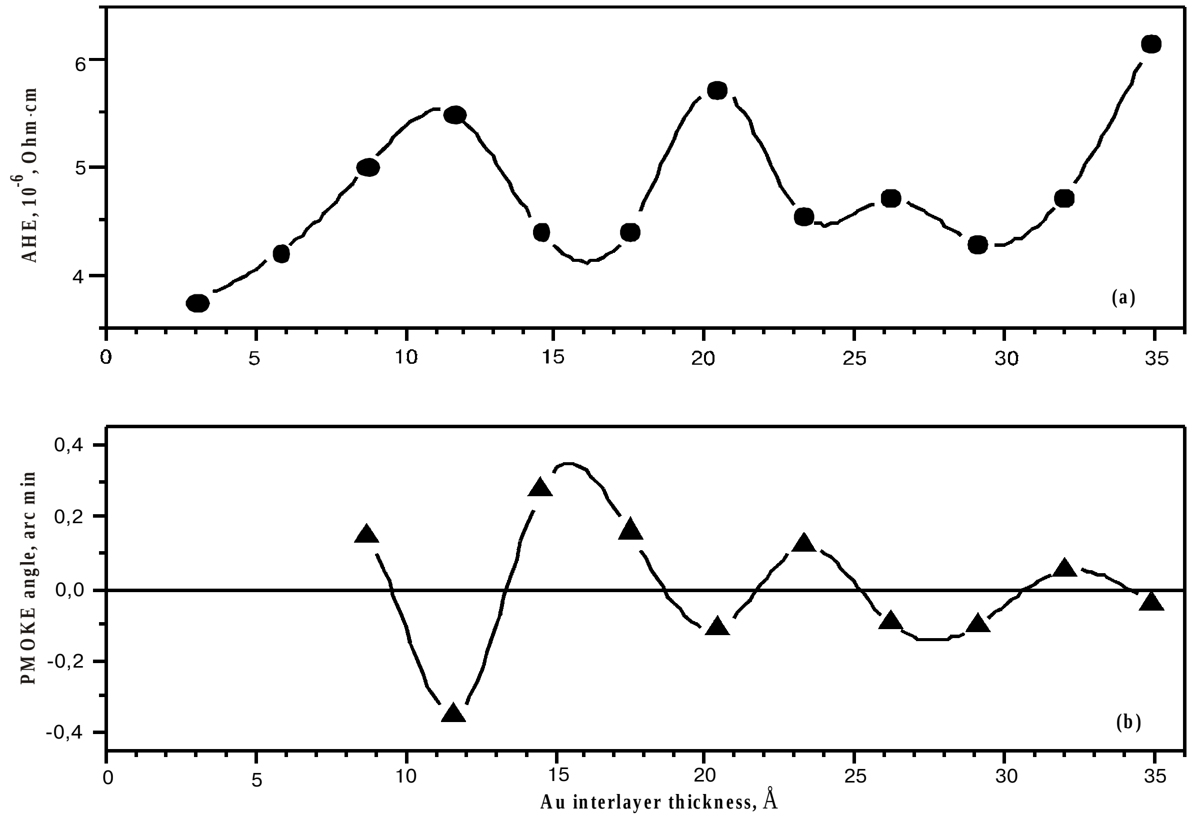

Fig. 4. Oscillations of the a) PMOKE angle for Fe/x Au/Tb trilayers in comparison with b) the anomalous Hall effect resistivity for the same structures [33]

4. Conclusions

As a result of investigations, it was confirmed that PMA of Fe-Tb system is determined by the short-range interaction between Fe and Tb atoms at the interface. It was shown that introduction of only one Au monolayer into the single Fe-Tb interface drastically affects magnetic interactions, entirely destroying short-range interactions. Instead, the long-range indirect exchange interaction through the Au spacer appears.

The increase of the Au spacer thickness (3 ÷ 35 Å) results in the oscillation of the Kerr angle. Analogous oscillations are distinctive to the RKKY model of interlayer exchange coupling.

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