Temperature induced interface roughness and spin reorientation transition in Co/Au multilayers thin films

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Abstract
Spin reorientation transition (SRT) due to high temperature has been studied in Co/Au multilayered thin films. The effect of temperature on structural and magnetic properties of the thin films has been investigated. Film thickness and interface roughness has been studied by measuring x-ray reflectivity. Multilayers are thermodynamically stable, and thickness of the layers and interface roughness remains unchanged over longer periods of time as well as up to a temperature of 300 °C. An increase in interface roughness at higher temperatures indicates intermixing of Co and Au into each other. Behavior of coercive field for both the samples is quite different. However, the spin reorientation transition occurred in both the samples around 350 °C. Here we are reporting our study on temperature induced spin reorientation transition in Co/Au multilayers. A spin reorientation transition is observed from out-of-plane to in-plane direction for 12 Å thick Co layer sample at 350 °C and a reverse transition is observed for 25 Å thick Co layer sample. Results were obtained using ex situ and in situ Magneto-Optic Kerr Effect (MOKE) measurements.

1. Introduction

Magnetic thin films, specifically nanoscale structures, attract great attention both for their technological applications and for fundamental research [1–3]. For example, several magnetic super lattices, such as, Co/Au [4, 5], Co/Pd [6], Co/Pt [7] and Co/Cu [8, 9] exhibit various magnetic properties like interlayer exchange coupling [4], Giant magnetoresistance [10], magnetic anisotropy [11], exchange bias [12] etc. The magnetic properties are influenced by film thickness, crystalline anisotropy and surface/interface roughness etc inasmuch as the surface/interface roughness alone influences many properties like magnetic anisotropy, magnetic moments, saturation magnetization and coercivity [13, 14]. In multilayers, the interface roughness depends on parameters like deposition rate, nature of the deposition, type of substrate, nature of buffer layer and capping layers used. Various theoretical and experimental investigations have been done to understand the effects of surface interface roughness on magnetic properties, such as, perpendicular magnetic anisotropy (PMA) [5], spin reorientation transition [4] and exchange bias [12]. Multilayers exhibiting PMA are used in data storage devices. This suggests that, the strength of the perpendicular magnetic anisotropy depends on quality of the interface [15]. Hence, crystallographic modification is an excellent tool for tuning such properties [3]. Ion-radiation [13] and thermal treatment [16] have been reported to be the most efficient ways to modify surface and interface micro-structure. Any change in the ordering of bilayers [17], use of different types of buffer layer [9] and addition of surfactants [8, 18] have also been reported to enhance the surface and interface structure effectively.

Co-Au interface has been extensively studied in recent years. These studies have been carried out, with the help of techniques like low energy electron diffraction [19] and scanning tunneling microscopy [20], in order to understand the formation of Co-Au interface. Yauichi Haruyama et al [21] performed a systematic study on Au-Si interface by observing electronic structures at the interface as a function of annealing temperature. They observed that composites of Au-Si were formed at the interface. Diffusion of Au into Si substrate was further
studied extensively in presence of oxygen, bromine and hydrogen subsequently [22]. However, limited work has been reported on Co-Au interfacial structures. Interface roughness has always been of prime focus of investigations since it determines the quality of a multilayer from scientific perspective [23]. Although the role of interface on magnetic properties has been extensively studied [24–26], the evolution of interface roughness on multilayers or the effect of growth mechanisms on interface roughness have not been sufficiently addressed.

Co-Au interface are immiscible and have high lattice mis-match of over 14% and possess a rough interlayer in their as grown state [27]. It is expected that annealing effectively monitors the interlayer structure formed by Co-Au layers [28]. With recent advancements in deposition techniques, it is possible to obtain ultra-thin interfaces with minimal interface roughness. Spin reorientation as a function of Co layer thickness in Co-Au multilayer has been discussed by Marcatoma et al [4]. In a recent report Kumar et al [29] studied the effect of annealing temperature on Fe film sandwiched between Au and Si, while Putter [30] studied the thickness dependent reorientation transition Co/Au multilayer.

Our aim is to explore the possibility of spin reorientation in Co-Au multilayer as function of heating temperature. In this article the effect of temperature on interface roughness and magnetic properties of Co-Au multilayers has been studied using in situ measurement techniques. In-situ studies were done as a function of heating temperature. Ex-situ experiments were also performed at room temperature. Ex-situ measurements were completed just after deposition of multilayers, while in situ measurements, as function of temperature, were performed on the samples kept in vacuum desiccator for almost a year. Our intention was to also study the effect of time on the samples.

2. Experimental details

Two samples of Co-Au multilayers were deposited on silicon substrates using dc-magnetron sputtering. The compositions are Si\(_{100}\)[Cr\(_{200}\)Å/Au\(_{100}\)Å]\(_{10}\), Co\(_{x}\)Å/Au\(_{30}\)Å\(_{10}\) where, \(x = 12 \text{ Å and } 25 \text{ Å} \) respectively. Deposition of different elements was carried out in Ar atmosphere at \(2 \times 10^{-3} \text{ torr} \). Circular targets of diameter 6 cm of Co and Cr with purity 99.999% and circular target of diameter 3 cm of Au of purity 99.9999% were used for deposition. All the targets were thoroughly cleaned before sputtering. Chromium layer was deposited at a rate of 0.66 Å s\(^{-1}\) on silicon substrate. Gold deposition rate was kept at 0.13 Å s\(^{-1}\), while deposition rate of Co was 1.4 Å s\(^{-1}\). The substrates were oscillated linearly with respect to the central position of target for better uniformity of deposition. Cr was also used as buffer layer with Au. Formation and structure of the films were characterized by room temperature x-ray diffraction (XRD) taken at room temperature. The results of x-ray reflectivity (XRR) were used to determine thickness of layers and to study interface roughness. Magneto-Optic Kerr Effect (MOKE) magnetometer was used to record magnetic behavior.

XRR and MOKE for ex situ measurements were done at room temperature. MOKE measurements carried out applying magnetic field in-plane as well as out-of-plane geometry. Whereas high temperature in situ measurements were done in ultra-high vacuum (UHV) chamber designed for in situ studies. The temperature was gradually varied from room temperature (RT) to 450 °C and was closely monitored throughout the measurement. Since the rate of increase of temperature is very small, it is expected to not influence the results. XRR and MOKE data were recorded at a step of 50 °C. MOKE measurements were taken using He-Ne laser with an electromagnet capable of producing variable magnetic field of 100 mT in either direction in-plane geometry only.

3. Results and discussion

3.1. X-rays diffraction

Figure 1 shows the x-ray diffraction patterns of the two samples. Data were recorded for wide range of 2\(\theta\), but we are interested in the region near hcp Co (0002) and fcc Au (111) diffraction peaks only. The strongest multilayer reflection peak in both the samples are denoted by −1, 0 and 1, using same nomenclature used by [27]. In the studied samples it is difficult to observe distinct peaks corresponding to hcp Co (0002) and fcc Au (111) because the thickness of the layers is very less. But, in our samples, we observed a diffraction peaks for both in the vicinity of Au fcc (111). The peak position gives an average d spacing of crystalline structure of Co and Au layers. For 12 Å thick Co layer, peaks corresponding to Au and Co are very close to each other and is dominated by diffraction peak (denoted by 0) of Au layer. But in 25 Å thick Co layer multilayer both the peaks are separated. It is also evident, from XRD pattern, that in thicker Co layer sample peak has shifted towards higher angles, because lattice parameter of Co is less than that of Au. Some satellite peaks are also observed. Presence of these satellite peaks confirmed good quality of multilayer [27].
Figure 1. Room temperature XRD graphs of (a) 25 Å thick and (b) 12 Å thick Co layers multilayers. The strongest multilayer reflection peaks in both the samples are denoted by -1, 0 and 1.

Figure 2. XRR measurement of 12 Å thick Co layer sample (a) in situ (red colour line) and ex situ (black line) XRR graphs (b) Scattering length density (ρ) depth profile calculated using Parratt formulism.
Figure 3. XRR measurement of 25 Å thick Co layer sample (a) in situ (red colour line) and ex situ (black line) XRR graphs (b) Scattering length density ($\rho$) depth profile calculated using Parratt formalism.

Figure 4. In-situ XRR graphs of 12 Å thick Co layer sample taken at different temperatures.
Figure 5. *In-situ* XRR graphs of 25 Å thick Co layer sample taken at different temperatures.

Figure 6. Variation of film thickness and interface roughness (a) 12 Å and (b) 25 Å thick Co layer sample.
3.2. X-ray reflectivity

Thickness of the layers, interface between the film and the substrate and the roughness of interface were estimated using x-ray reflectivity (XRR). A comparison between XRR measurement of as-prepared sample and those kept for one year in desiccator is shown in figures 2(a) and 3(a). The periodic oscillations (Keissig fringes) in wings indicate a very small change in surface/interface roughness, which is well within the experimental error of ± 0.5 Å. Ex-situ as well as in situ data were analyzed and scattering length density (SLD) is determined from XRR data using Parrot method. There is no difference in SLD obtained from the two data. SLD is plotted as function of thickness of layers and shown in figures 2(b) and 3(b). The frequency of oscillations of SLD confirms the thickness of Au and Co layers. The amplitude of SLD has same value at the middle of layers indicating the uniformity of deposited layers.

Effect of temperature on interface roughness was studied using in situ XRR measurement. Figures 4 and 5 show the XRR patterns of 12 and 25 Å thick Co layer samples respectively. These graphs show the intensity of reflected x-ray from thin films samples as a function of magnitude of momentum transfer vector, $q_d = (4\pi \sin \theta)/\lambda$, where $\theta$ is incident angle of x-rays and $\lambda$ is its wavelength. Periodic oscillations (Keissig fringes) were observed in XRR patterns with first maxima appearing at $q_d = 0.188$ and 0.148 for 12 Å and 25 Å thick Co layer samples respectively. The peak positions of fringes from observed reflectivity data are used to estimate the thickness of the film using the modified Bragg’s equation,
where $\theta_i$ is the observed position of maxima or minima of $i$th fringe, $\theta_C$ is critical angle for total reflection, $n_i$ is an integer, the value of $\Delta n$ is $\frac{1}{2}$ or 0 for maxima or minima respectively and $\lambda$ is the wavelength of x-ray used [31].

Well resolved Keissig oscillations in XRR graphs show that the film has homogenous thickness.

It is evident from this graph that intensity of XRR pattern remains almost unchanged up to 300 °C and slightly decreased at 350 °C. This observation shows that there is almost no change in the thickness of Co layer and interface roughness up to this temperature. On further heating at 400 °C, intensity of XRR peaks drops down drastically which indicates a sudden change in the interface structure. To make it more quantitative XRR data were fitted using Parratt formalism. Fitting gives thickness of the layers and interface roughness. Thickness of Co layer and interface roughness were plotted as a function of temperature and shown in figure 6. Initially the rms interface roughness was 5.7 Å and 10.1 Å for 12 Å and 25 Å thick Co layer samples respectively. The rms interface roughness obtained by the best fit using Parratt formalism shows variations in the higher temperature range. On heating beyond 380 °C, roughness of the films increases and became more than the thickness of Co layer in 12 Å thick sample. The interface roughness is around 5.5 Å and 10 Å in 12 Å and 25 Å Co layer samples respectively which increases to around 7.7 Å in 12 Å and around 13.5 Å in 25 Å sample. This could be because of mixing or inter-diffusion of Co and Au atoms into each other, leading to increase in roughness of interface. Both the studied samples show similar trends on heating. Deeder et al [3] have also mentioned inter-diffusion in their Co/Fe thin films due to higher temperature. They also mentioned that up to almost 300 min of annealing at 350 °C, no appreciable change is observed in rms interface roughness while interdiffusion may have occurred during this time. In our case too, there is not much change in rms interface roughness before diffusion process starts. But once the diffusion starts between the layers, interface roughness becomes dependent on the annealing time. It is also believed that short annealing time may not have a significant effect as compared to long annealing.
times. It is observed that, because of inter-diffusion, rms interface roughness increases after heating beyond 350 °C. This is also evident in coercivity trends as discussed in next section. In oxide multilayers, Nistor et al.\textsuperscript{[32]} showed that rms interface roughness increases due to hybridization between two adjacent layers at the interface. The possibility of hybridization is minimal in our case as we have pure metal.

3.3. Magneto-optic kerr effect (MOKE)

\textit{Ex-situ} MOKE data were recorded immediately after deposition of the multilayer films. Hysteresis loops were measured by applying magnetic field along the plane (in-plane geometry) and perpendicular to the plane (out-of-plane geometry) of the film. Loops obtained in both the cases are shown for 12 Å in figure 7(a) and for 25 Å in figure 7(b) thick Co layer samples. In both the figures it is difficult to differentiate the loops recorded in-plane or out-of-plane geometry. This observation indicates that the spins are randomly oriented, and hence, they can be aligned in any direction depending on the direction of applied magnetic field.

Effect of temperature on magnetic properties of the multilayers has been studied by recording \textit{in situ} MOKE parallel to XRR. \textit{In-situ} data were recorded almost a year after the preparation of the samples. Samples were heated till 420 °C and MOKE data were recorded at various temperatures by applying maximum field of 30 mT along the plane. MOKE graphs are given in figure 8 for 12 Å thick Co layer sample. In this sample no hysteresis loop is observed till the heating temperature of 350 °C. Since the magnetic field is applied in-plane direction, so if spins were aligned in-plane direction or in random direction then we would have observed a hysteresis loop till...
This signifies that spins are frozen 'out-of-plane' of the multilayer surface up to 350 °C. It has been discussed by Marcatoma et al [4] that the spins are preferentially oriented 'out-of-plane' in the samples if Co layer thickness is less than 10–12 Å, and spins are aligned 'in-plane' beyond this thickness. Our observations are also consistent with their findings. It is clear from figure 8 that a magnetic field of 30 mT is not adequate to reorient the spins along 'in-plane' direction even up to 350 °C temperature, and hence no hysteresis loop has been observed. Once the temperature goes beyond 350 °C, thermal energy becomes sufficient enough to break frozen-in spin state or reorient the spins hence, we obtained the hysteresis loop. It is interesting to note that the hysteresis loop saturates at very low applied field indicating that spins are now reoriented in-plane geometry around 350 °C in 12 Å thick Co layers multilayer.

Further, this sample continues to respond to magnetic field till the heating temperature of 415 °C and coercivity is observed to increase. The shift in hysteresis loop at 420 °C can be associated with the exchange bias behavior due to possible formation of CoO at the top surface. On further increase in temperature we are unable to observe any hysteresis loop. It is important to note that intermixing of Co and Au into each other may have happened around 370 °C, but hysteresis loop disappeared only after 420 °C. This could be possibly be because magnetic-nonmagnetic transition temperature may be higher than 370 °C and hence, we continue to observe loop up to 420 °C. At such higher temperatures thermal energy dominates over magnetic energy and the field applied in this experiment is not enough to align the moments in the direction of applied magnetic field which leads to disappearance of loop.

However, the magnetic behavior of the multilayer sample with 25 Å thick Co layer is quite different. When magnetic field is applied along the plane of this multilayer, a complete hysteresis loop is observed at room temperature. This is because spins are aligned along 'in-plane' direction for this sample [4, 27, 33]. Figure 9 shows MOKE measurement of this sample, it is clearly seen in this figure that MOKE intensity quickly reaches to saturation confirming that spins were already aligned themselves in 'in-plane' geometry. On increasing the

![Figure 10. Variation of coercive field (Hc) and saturation field (Hs) (a) 12 Å and (b) 25 Å thick Co layer sample.](image-url)
temperature, nature of the loop remains same while coercive field decreases. There is a continuous decrease in coercivity as a function of temperature. This decrease in coercivity can be associated with small increase in thermal energy that perhaps helps domain wall motion up to 350 °C. This is evident from the hysteresis loop. Beyond 350 °C, we obtained a close loop only after applying a relatively higher field and the loop does not look like a typical hysteresis loop. This suggests that beyond 350 °C spins get reoriented 'out-of-plane' and very high field is required to bring them back to 'in-plane' direction. Disappearance of hysteresis loop in 25 Å thick Co layer sample and appearance of it in 12 Å thick Co layer sample at 350 °C is a clear indication of spin reorientation transition in samples. In our study, spin reorientation transition from 'out-of-plane' to 'in-plane' direction in 12 Å, while 'in-plane' to 'out-of-plane' in 25 Å thick Co layer sample at 350 °C is observed.

On heating beyond 420 °C, multilayers did not respond anymore to the applied magnetic field. This could be due to loss of magnetic interaction between Co-Co atoms. It has been discussed in XRR section that above 420 °C, surface roughness increases because of intermixing of Co and Au atoms. Once Co and Au atoms mix into each other, the number of Co-Co nearest neighbours decrease. Also, at higher temperatures thermal energy dominates over magnetic energy and hence magnetic ordering is lost. This results in disappearance of MOKE intensity.

Coercivity (Hc) and saturation field (Hs) (the applied field, at which the MOKE intensity saturates), has been calculated from the MOKE data. Usually in thin films the saturation field is close to coercive field in absence of anisotropy in the system. In the current study the saturation field is measured where MOKE intensity reaches its maximum value. There are fluctuations in the MOKE intensity beyond applied field of ±10 mT (figure 8). The variation in coercive field (Hc) and saturation field (Hs) with temperature is shown in figure 10. For 25 Å thick Co layer sample (figure 10(b)) a coercivity of about 11 mT is observed at room temperature and decreases continuously before spin reorientation has taken place. Separate analysis will be performed to study the dependence of coercivity with temperature.

4. Conclusion

The effect of high temperature on surface interface roughness and magnetic properties has been studied in the Co/Au multilayers. Both the studied samples are highly stable and retained the thermodynamically stable crystalline structure. In conclusion, we can say that

1. In the studied samples, thickness and interface roughness remain almost same till the heating temperature of 350 °C.
2. In as-prepared samples, spins are randomly oriented on the surface, but they align themselves along 'out-of-plane' direction in 12 Å thick Co layer sample and 'in-plane' direction in 25 Å thick Co layer samples.
3. A spin reorientation transition has been observed after 350 °C in both the samples.
4. Disappearance of magnetic interaction between Co–Co atoms in both the samples beyond 420 °C indicates the intermixing of Co and Au atoms in to each other.

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References

[1] Tekielak M, Mazalski P, Maziweski A, Schafer R, McComb I, Szymbanski B, Urbaniaik M and Stobiecki F 2008 Creation of out-of-plane magnetization ordering by increasing the repetitions number N in (Co/Au)N multilayers IEEE Trans. Magn. 44 2850–3
[2] Bontempi E and Depero L E 2004 A XRD study of Co/Au multilayers using a laboratory microdiffractometer Thin Solid Films 450 183–6
[3] Aurongzeb D, Bhargava Ram K and Menon I 2005 Influence of surface/interface roughness and grain size on magnetic property of Fe/Co bilayer Appl. Phys. Lett. 87 172509
[4] Quispe-Marcatoma I, Pandey B, Alayo W, de Sousa M A, Pelegrini F and Baggio Saitovitch E 2013 Preferential orientation of magnetization and interfacial disorder in Co/Au multilayers J. Magn. Magn. Mater. 344 176–81

[5] Stobiwcki F, Urbaniai M, Tekielak M, Szyszmannski B, Lucinski T, Schmidt M and Maziewski A 2007 Interlayer coupling in Ni–Fe/Au/Co/Au multilayers J. Magn. Magn. Mater. 310 2292–4

[6] Garcia P, Meinholdt A and Suna A 1985 Perpendicular magnetic anisotropy in Pd/Co thin film layered structures Appl. Phys. Lett. 47 178–80

[7] Stillrich H, Menk C, Frontier R and Oepen H P 2009 Magnetic anisotropy and the cone state in Co/Pt multilayer films J. Appl. Phys. 105 07C308

[8] Stalin S M A, Gupta M and Gupta A 2013 Surfactant controlled interface roughness and spin-dependent scattering in Co/Co multilayers Appl. Phys. A 111 495–9

[9] Bouziane K, Al Rawas A D, Maaza M and Mamor M 2006 Buffer effect on GMR in thin Co/Cu multilayers J. Alloys Compd. 414 42–7

[10] Parkin S S P, Farrow R F C, Marks R F, Cebollada A, Harp G R and Savoy R J 1994 Oscillations of interlayer exchange coupling and giant magnetoresistance in (111) oriented permalloy/Au multilayers Phys. Rev. Lett. 72 5718

[11] Chubing P, Daosheng D and Ruiyi F 1992 Magnetic anisotropy and interlayer exchange coupling of evaporated Au/Co multilayers Phys. Rev. B 46 12022

[12] Zhang F, Liu Z Y, Wen F S, Li L, Wang P W, Li X C and Ming X B 2017 Exchange biasing and interlayer coupling in Co/Pt/Co/CuO multilayers with perpendicular anisotropy Thin Solid Films 523 102–9

[13] Zhao Y P, Gamage R M, Wang G C and Lu T M 2001 Effect of surface roughness on magnetic domain wall thickness, domain size and coercivity J. Appl. Phys. 89 1325–30

[14] Lee C H, He H, Lamelas F, Vavra W, Uher C and Clarke R 1969 Epitaxial Co-Au superlattices Phys. Rev. Lett. 62 653

[15] Krams P, Hillebrandt B and Guntherodt G 2010 Magnetic field dependent coercivity J. Appl. Phys. 69 5807–9

[16] Menon L, Patibandla S, Bhargava Ram K, Shkuratov S, Aurongzeb D, Holtz M, Berg J, Yun J and Temkin H 2004 Ignition studies of Al/Fe3O4 energetic nanocomposites Appl. Phys. Lett. 84 4735–7

[17] Park M H, Hong Y K, Lee S H, Mottern M L and Jang T W 2002 Difference in coercivity between Co/Fe and Co/Cu bilayers J. Appl. Phys. 91 7218–20

[18] Kamiko M, Nakamura A, Aotani K and Yamamoto R 2009 Bi surfactant effects of Co/Cu multilayered films prepared by sputter deposition Appl. Surf. Sci. 256 1257–60

[19] Allenspach R, Stamparoni M and Bischof A 1990 Magnetic domains in thin epitaxial Co/Au (111) films Phys. Rev. Lett. 65 3344

[20] Chizhov I, Geusebroeck Lee I and Willis R F 1997 Initial stages of Au adsorption on the Si (111) (7 × 7) surface studied by scanning tunneling microscopy Phys. Rev. B 56 12316

[21] Haruyama Y, Kanda K and Matsui S 2007 Electronic and geometric structures of the Au–Si(1 0 0) surface observed by photoemission spectroscopy and LEED J. Electron. Spectrosc. Relat. Phenom. 156 463–6

[22] Bal J K and Hazra S 2007 Interfacial role in room-temperature diffusion of Au into Si substrates Phys. Rev. B 75 205411

[23] Paul A, Damm T, Burger D E, Stein S, Kohlstedy H and Grunberg P 2003 Correlation of magnetotransport and structure in sputtered Co/Cu multilayers J. Phys. Condens. Matter 15 2471

[24] Jiang Q, Yang H N and Wang G C 1997 Effect of interface roughness on hysteresis loops of ultrathin Co films from 2 to 30 ML on Cu (001) surfaces Surf. Sci. 373 181–94

[25] Ruffino F and Grilliardi M G 2010 Atomic force microscopy study of the growth mechanisms of nanostructured sputtered Au film on Si (111): evolution with film thickness and annealing time J. Appl. Phys. 107 104321

[26] Gupta A, Paul A, Chaudhuri S M and Phase D M 2000 Effect of interface roughness on GMR in Fe/Cr multilayers J. Phys. Soc. Jpn. 69 2182–7

[27] Den Broeder F J A, Kuiper D and Van de Mosselaer A P 1988 Perpendicular magnetic anisotropy of Co–Au multilayers induced by interface sharpening Phys. Rev. Lett. 60 2769

[28] Gubbiotti G, Carlotti G, Albertini F, Casoli F, Botempi I E, Depero H K and Gomez R D 2003 Influence of annealing on Co/Au multilayers: a structural and magnetic study Thin Solid Films 428 102–6

[29] Yogesh Kumar J, Tripathi S, Tripathi D, Kumar R, Bison K C and Ugocshukwu A 2018 Sharma, Influence of annealing on the structural and magnetic properties of Fe thin film sandwiched between Au and Si Vacuum 153 221–4

[30] Putter S 2019 Orthogonal bistable magnetic structures in Co/Au bilayers J. Magn. Magn. Mater. 492 165648

[31] Huang T C, Gilles R and Will G 1993 Thin-film thickness and density determination from X-ray reflectivity data using a conventional power diffractometer Thin Solid Films 230 99–101

[32] Nistor I E, Rodmacq B, Auffret S and Dieny B 2009 Pt/Co/Oxide and Oide/Co/Pt electrodes for perpendicular magnetic tunnel junctions Appl. Phys. Lett. 94 012512

[33] Quispe-Marcatoma I, Tarazona H, Pandey B, de Sousa M A, Carvalho M, Landauero C V, Pelegrini F and Baggio Saitovitch E 2014 spin reorientation transition in Co/Au multilayers Thin Solid Films 568 117–21