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Composition-Morphology-Property Relations For Giant Magnetoresistance Multilayers Grown By RF Diode Sputtering

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ABSTRACT

A series of experiments have been conducted to evaluate the magnetotransport properties of RF diode sputter deposited giant magnetoresistive (GMR) multilayers with either copper or copper-silver-gold nonferromagnetic (NFM) conducting layers. The study revealed that RF diode deposited multilayers utilizing $Cu_{80}Ag_{15}Au_5$ as the NFM conducting layer posses significantly superior giant magnetoresistance to otherwise identical device architectures that used pure copper as the NFM conducting layer. To explore the origin of this effect, copper and $Cu_{80}Ag_{15}Au_5$ films of varying thickness have been grown under identical deposition conditions and their surface morphology and roughness investigated. Atomic force microscopy revealed significant roughness and the presence of many pinholes in thin pure copper films. The surface roughness of the $Cu_{80}Ag_{15}Au_5$ layers was found to be much less than that of pure copper, and the alloying eliminated the formation of pinholes. Molecular statics estimates of activation barriers indicated that both silver and gold have significantly higher mobilities than copper atoms on a flat copper surface. However, gold is found to be incorporated in the lattice whereas silver tends to segregate (and concentrate) upon the free surface, enhancing its potency as a surfactant. The atomic scale mechanism responsible for silver's surface flattening effect has been explored.

1. INTRODUCTION

Metal multilayers consisting of alternating ferromagnetic (FM) and nonferromagnetic (NFM) metals sometimes exhibit large changes in their electrical resistance when a magnetic field is applied [1-10]. The effect results from a change in their spin dependent electron scattering when an applied magnetic field rotates the magnetic moment of one of the ferromagnetic layers [1-10]. Devices utilizing it are widely used as the magnetic field sensors in hard disk drive read heads [4]. Related devices are being investigated for use as magnetic random access memories (MRAM) [4]. Current GMR multilayers appear not to have achieved their performance upper bound. Reducing both the smoothness and chemical diffuseness of the interfaces in GMR multilayers appear to be particular important [2,8]. Achieving materials with a large GMR ratio at a low saturation field therefore requires the use of materials, layer thickness and deposition conditions that minimize interfacial roughness.

2.EXPERIMENTS

The study has focused upon the influence of the nonferromagnetic conducting layer composition (either Cu or $Cu_{80}Ag_{15}Au_5$) on the GMR ratio and the saturation field of RF diode sputter deposited GMR multilayers. Multilayers with either Cu or $Cu_{80}Ag_{15}Au_5$ NFM conducting layers together with, 100, 500 and 1000Å thick Cu and $Cu_{80}Ag_{15}Au_5$ single layer films were grown at Nonvolatile Electronic, Inc. (Eden Prairie, MN) using a Randex Model 2400-6J RF diode system. Briefly, the diameter of the targets was 20.32cm, the distance between substrate and target was 3.81cm, the pressure was 20mTorr and a 175W power was used for growth of all the multilayers and the Cu and $Cu_{80}Ag_{15}Au_5$ single layer films.

The architecture and compositions of the antiferromagnetically coupled multilayers are shown in Figure 1. The multilayers contained three repeated exchange coupled layer stacks. Each layer stack was a composite of two ferromagnetic layers ($Ni_{65}Fe_{15}Co_{20}$ and $Co_{95}Fe_5$) arranged so that the $Co_{95}Fe_5$ layer was at the interface with either the copper or copper alloy layer. In each case a fixed NFM conducting layer thickness of 16Å was used.

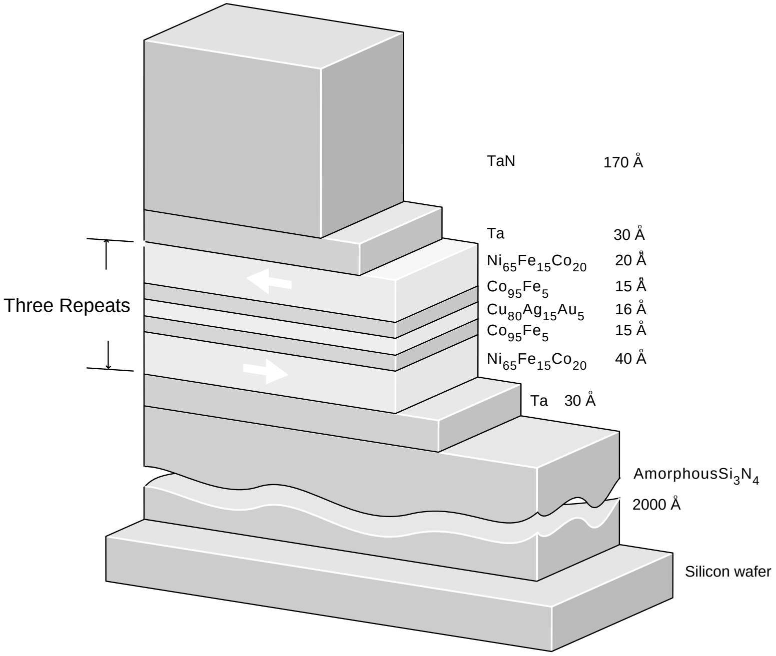


Figure 1 The GMR multilayer structure studied here. Layer compositions and thicknesses are shown. Arrows indicate the magnetic alignment of the ferromagnetic alloy layers.

3. Experimental Results

Figure 2 shows the dependence of the GMR ratio and saturation field upon the number of repeated stacks in the Cu and $Cu_{80}Ag_{15}Au_5$ conducting layer multilayers. The magnetoresistance change is usually characterized by the GMR ratio which is the resistance change scaled by the zero field resistance. The saturation magnetic field is the strength of the smallest applied magnetic field needed to achieve the GMR ratio. The results in Figure 2 show that multilayers grown with a pure Cu conducting layer exhibited no GMR effect, whereas multilayers grown with a $Cu_{80}Ag_{15}Au_5$ conducting layer had significant GMR ratios. The saturation magnetic field of the $Cu_{80}Ag_{15}Au_5$ multilayers also increased with the number of stacks. Both the GMR ratio and the saturation fields are reasonable well suited for the magnetic sensing applications [3,4,8]. Many researchers have successfully used pure Cu as conducting layer in GMR multilayers. They used a different deposition approach [4] and the Cu layer thickness was usually greater than 20Å. For the particular architecture and composition of the multilayer and RF diode deposition equipment investigated here, Cu thickness below 20Å resulted in no GMR [3].

To explore the reasons for the loss of the GMR effect, three different thickness Cu and $Cu_{80}Ag_{15}Au_5$ single layer films were grown under the same deposition conditions to the multi-layers. The surface morphology of each film was then evaluated with tapping mode atomic force microscopy (AFM), Figure 3. The scan size was 1µm x 1µm and scan rate was 1 Hz for all the films. These results revealed periodic surface roughness with an asperity width that increased with the film thickness in both types of films, Figure 3. However, the Cu films had a larger asperity widths and higher surface amplitudes than their $Cu_{80}Ag_{15}Au_5$ counterparts. Pinholes (the dark spots on the image) were present in the 100Å thick Cu film, Figure 3(d). AFM measurements indicated the average depth of the pinholes was at least 40Å. Their diameter was approximately 800Å. No pinholes were observed in CuAgAu films. Figure 3. Figure 4 shows the RMS roughness increased with the film thickness in both the Cu and $Cu_{80}Ag_{15}Au_5$ films, but the Cu films were always much rougher. The loss of the GMR effect in multilayers with a pure copper conducting layer is consistent with ferromagnetic layer coupling through pinholes in the NFM spacer layer [3].

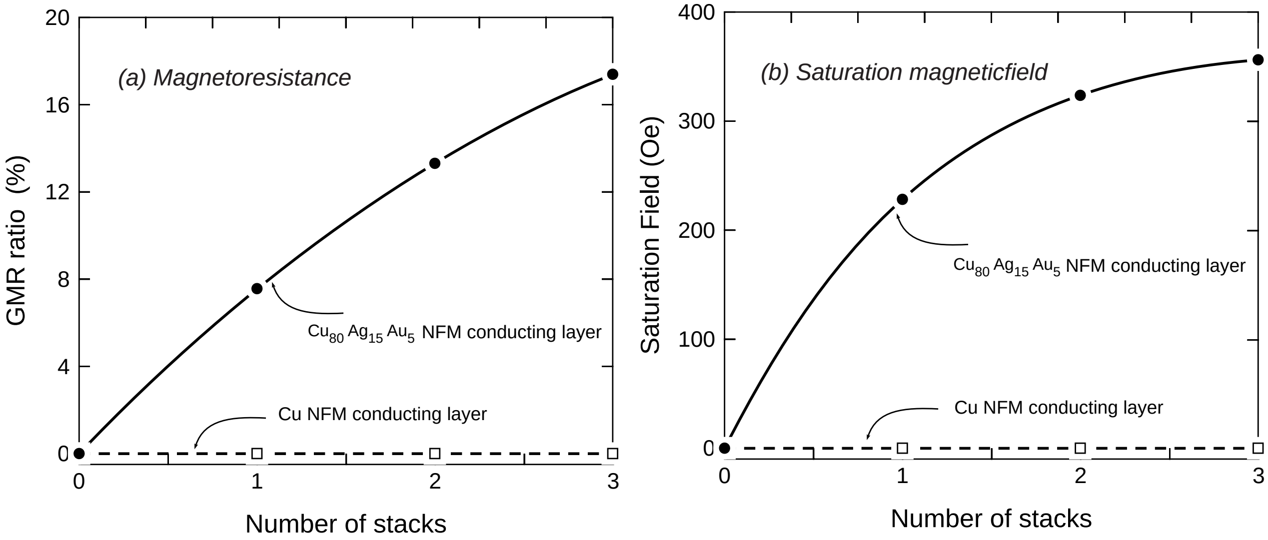


Figure 2 **The dependence of (a) the GMR ratio, and (b) the saturation field upon the number of repeated multilayer stacks for Cu and $Cu_{80}Ag_{15}Au_5$ NFM conducting layers. In each case a fixed NFM conducting layer thickness of 16Å was used. Multilayers grown with a pure Cu NFM conducting layer exhibited no giant magnetoresistance. Multilayers grown with a $Cu_{80}Ag_{15}Au_5$ as conducting layer possessed significant GMR ratios.**

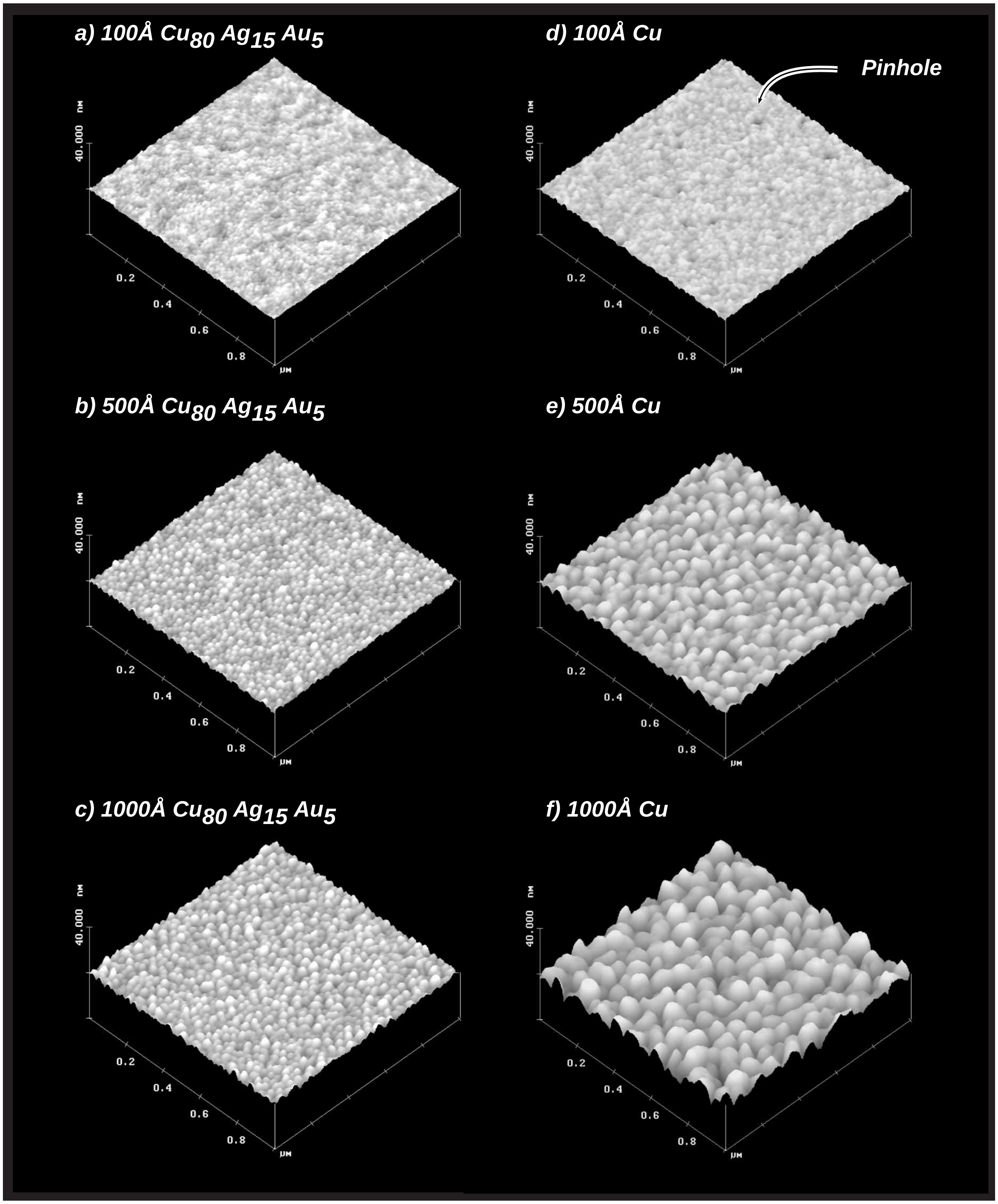


Figure 3 **The topography of $Cu_{80}Ag_{15}Au_5$ and pure Cu films of different thicknesses. The growth column width increased with the film thickness for both film types. The pure Cu films have a larger growth column width, and a rougher surface compared to $Cu_{80}Ag_{15}Au_5$ films of identical thickness.**

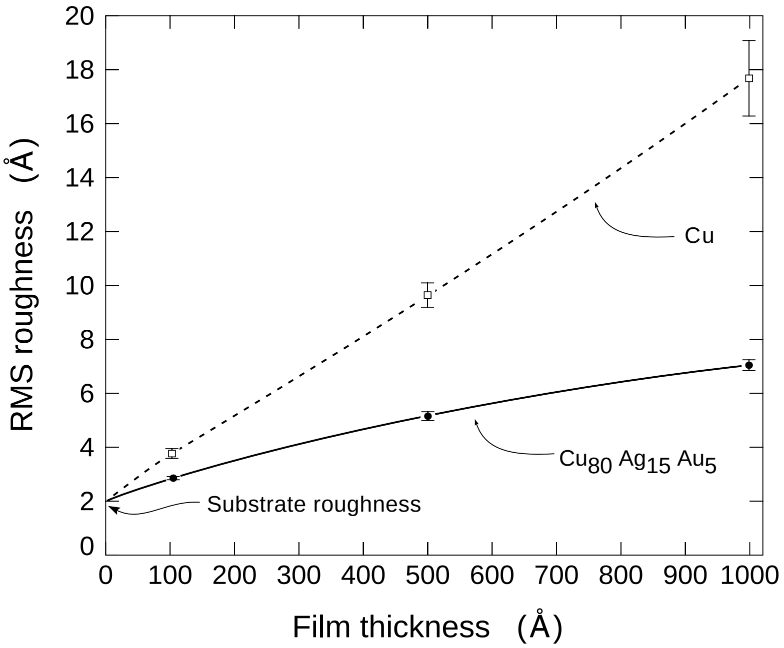


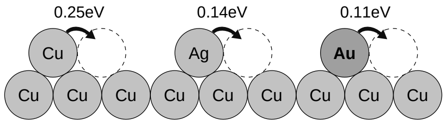
Figure 4 The RMS roughness increases with the film thickness for both Cu and $Cu_{80}Ag_{15}Au_5$ film. The pure Cu films are much rougher compare to the $Cu_{80}Ag_{15}Au_5$ films.

4. Discussion

Using the 3D EAM as a starting potential, 2D molecular statics can be used to estimates activation barriers for the atom configuration dependent migration energies [9,10]. The barrier for the hopping of Cu on a smooth close-packed Cu surface was found to be 0.25 eV. The corresponding energies for Ag and Au on such a copper surface were only 0.14 and 0.11 eV respectively. If the jump attempt frequencies are assumed identical, Ag and Au have a much higher mobility on a Cu surface than Cu atoms, Figure 5 (a). These molecular statics estimates also indicated that the Ehrlich-Schwoebel barrier for Cu depends on which atom type is attached to the edges of ledges. When the edge of the ledge is either Cu, Ag or Au, the Ehrlich - Schwoebel is 0.35eV, 0.28eV, or 0.33eV respectively, Figure 5 (b). Silver at the ledge edge reduces the Ehrlich-Schwoebel barrier for copper to approximately the barrier for hopping on a close packed surface.

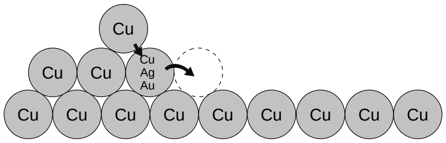
These molecular statics calculations also show that it is energetically favorable (by 0.15 eV/ atom) for a Au atom on a copper surface to exchange (and alloy) with a Cu atom, Figure 5 (c). They also show it is unfavorable (by 0.05 eV/atom) for Ag to exchange with copper. As a result, Au is likely to be buried in Cu whereas Ag trends to segregate to the surface which in agree with the MD simulation observations. The segregation of Ag appears beneficial since it maintains a high concentration of Ag at the surface [21-25]. This has the effect of increasing the mobility of atoms on the surface and enhances the probability that it will be attached to ledge edges where it can lower the Ehrlich-Schwoebel barrier for Cu atoms. This dramatically reduces flux shadowing and results in pinhole free films and smoother surfaces. Gold atoms also reduce the Ehrlich- Schwoebel barrier, but is not lowered as much as the silver, and no Au concentration enhancement at the surface occurs.

(a) Low Cu mobility and high Ag and Au mobility on Cu



(b) The Schwoebel barrier for Cu when the edge of the ledge is

Cu=0.35eV, Ag=0.28eV, and Au=0.33eV.



(c) Ag - Cu segregation and Au - Cu exchange

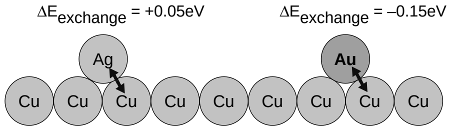


Figure 5 Alloy effects on atomic assembly. (a) low Cu and high Ag and Au mobility on Cu, (b) the Ehrlich-Schwoebel barrier for Cu when the edge of the ledge is Cu, Ag, and Au, (c) Au-Cu exchange and Ag-Cu segregation.

5. Summary

Radio frequency diode sputter deposition has been used to grow $Ni_{65}Fe_{15}Co_{20}$ /$Co_{95}Fe_5$/Cu or $Cu_{80}Ag_{15}Au_5$/$Co_{95}Fe_5$/$Ni_{65}Fe_{15}Co_{20}$ multilayers. Multilayers utilizing $Cu_{80}Ag_{15}Au_5$ as the nonferromagnetic conducting layer exhibited significant giant magnetoresistance whereas otherwise identical device architectures that use a pure copper conducting layer fail to exhibit any magnetoresistance. The cause is the AFM identified presence of pinholes in copper films but not in thin $Cu_{80}Ag_{15}Au_5$ films. Molecular statics analyses confirm that silver and gold atoms are very mobile and reduce the Ehrlich-Schwoebel barrier at a copper ledge. These changes both contribute to a smoother surface.

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