The effect of Ta on the magnetic thickness of permalloy ($Ni_{81}Fe_{19}$) films

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The effect of Ta and Ta/Cu seed layers, and Ta and Cu cap layers on the effective magnetic thickness of ultrathin permalloy ($Ni_{81}Fe_{19}$) was investigated for MRAM applications. The films were deposited by Ion Beam Deposition. The magnetic moment of each as-deposited permalloy film was measured using a B-H looper and a SQUID magnetometer. The films were further annealed at either 525 K for 1/2 h or 600 K for 1 h to study the effect of thermally driven interdiffusion on the magnetic moment of the permalloy film. Our theoretical calculations showed that the presence of 12% intermixing at the interface reduces the Ni moments to zero. Experimentally, it was shown that the tantalum rather than the copper interfaces are primarily responsible for the magnetically dead layers. The Ta seed layer interface produces a loss of moment equivalent to a magnetically dead layer of thickness 0.6 ± 0.2 nm. The Ta metal in the cap layer results in a loss of moment equivalent to a dead layer of thickness 1.0 ± 0.2 nm. Upon annealing, thermally driven interdiffusion is concluded to have a strong effect on the Ta(seed)/ $Ni_{81}Fe_{19}$ as-deposited interface, based on the doubling of the magnetically dead layer to 1.2 ± 0.2 nm. The $Ni_{81}Fe_{19}$/Ta(cap) as-deposited interface slightly increases its equivalent magnetically dead layer upon annealing to 1.2 ± 0.2 nm. As-deposited interfaces of Ta(seed)/permalloy and permalloy/Ta(cap) are not chemically equivalent and result in different magnetically dead layers, whereas after annealing to 600 K both interfaces attain comparable intermixing and magnetically dead layers. It was also shown that a half-hour anneal at the lower 525 K annealing temperature, which is closer to the actual processing temperature, results in only slight increase of the magnetically dead layer at both interfaces. © *2000 American Institute of Physics.* [S0021-8979(00)73808-4]

In this work, the effect of tantalum seed and cap layers on the magnetic thickness of permalloy is investigated in detail for MRAM (Magnetic Random Access Memory) applications. The MRAMs employ a PSV (Pseudo-Spin-Valve) structure which consists of two magnetic layers of unequal thickness separated by a nonmagnetic spacer. PSVs exhibit the well known GMR (Giant Magneto-Resistance) effect: The resistance across the trilayer film depends on the relative orientation of the top and bottom magnetic films. The effective magnetic thickness of the bottom (storage) and top (read) magnetic layers determines the switching fields of the read and write events. Thinner permalloy layers are desirable to lower switching fields and therefore currents needed to address a particular bit for reading or writing. Both the storage and the read layers typically have permalloy ($Ni_{81}Fe_{19}$) in direct contact with tantalum. Therefore, it is of technological interest to study the effects of Ta seed layers and Ta cap layers on the effective magnetic thickness of ultrathin permalloy ($Ni_{81}Fe_{19}$).

Experiments were designed to study the effect of the Ta seed and cap layers separately, as shown in Fig. 1. The films were deposited using a Commonwealth Scientific Ion Beam Deposition system, and the following structures, with permalloy thickness ranging from $d=2$ to 10 nm, were grown:

(i) 5 nm Ta(seed)/d nm $Ni_{81}Fe_{19}$/10 nm Ta(cap) and

(ii) 5 nm Ta/5 nm Cu/d nm $Ni_{81}Fe_{19}$/10 nm Cu to separate the influence of Ta and Cu layers on the permalloy and to exclude any possible effects of the permalloy/Cu and Cu/permalloy interfaces, and both

(iii) 10 nm Ta(seed)/d nm $Ni_{81}Fe_{19}$/10 nm Cu, to study the influence of the Ta seed layer;

(iv) 10 nm Ta(seed)/5 nm Cu/d nm $Ni_{81}Fe_{19}$/10 nm Ta(cap) to study the influence of the Ta cap layer.

Physical thicknesses were calibrated based on deposition rates. The magnetic moment of each permalloy film was measured using SHB109 B-H looper on a whole 6 in. wafer. The magnetic moments for films in series (iii) and (iv) were also measured on a Quantum Design SQUID magnetometer for 5 mm by 6 mm pieces cut from the same wafers. These films were further annealed at 600 K for 1 h to study the effect of thermally driven interdiffusion on the magnetic moment of the permalloy film.

As shown in Fig. 2, our theoretical studies of the magnetic structure of Ni-rich Ni-Ta alloys using the KKR-CPA method[1,2] show that, in the ideal random alloy limit, the average magnetic moment vanishes at 12% Ta concentration. Experimentally, as shown in Fig. 3(a) and 3(b), by comparing series (i) and (ii), it is evident that the Ta interfaces are

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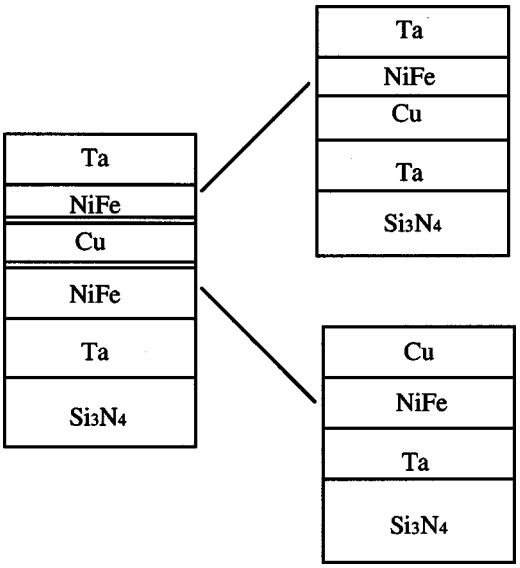

FIG. 1. Design of experiments to investigate separate effects of tantalum seed and cap layers on the magnetic moment of permalloy films used in the PSV. There are two types of Ta/permalloy interfaces: the bottom permalloy layer is deposited on top of a Ta seed layer (denoted as $Ta/Ni_{81}Fe_{19}$), whereas the top permalloy layer is covered by a deposited Ta cap layer (denoted as $Ni_{81}Fe_{19}/Ta$).

primarily responsible for the magnetically dead layers. The amount of missing moment in terms of equivalent magnetically dead layer was obtained from the horizontal axis intercept of the straight line dependence of magnetization as a function of the permalloy thickness. Permalloy layers surrounded by copper films exhibit virtually no loss of magnetic moment within the experimental error of 0.2 nm, whereas permalloy layers surrounded by tantalum films exhibit a 1.5 $\pm$0.2 nm magnetically dead layer. Series (ii) clearly shows that the moment of $Ni_{81}Fe_{19}$ is minimally reduced due to the

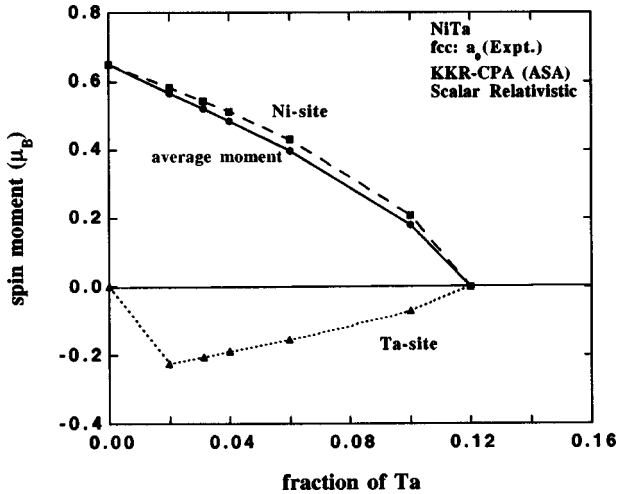

FIG. 2. Spin moment versus tantalum concentration in Ni-Ta alloy. Calculations were done at $l_{max}=3$ using scalar relativistic KKR-CPA and the atomic sphere approximation (ASA) method. Solid line represents alloy's average moment. The dashed and dotted lines show magnetic moment of Ni and Ta sites, respectively. The average moment in the alloy vanishes at 12% Ta concentration.

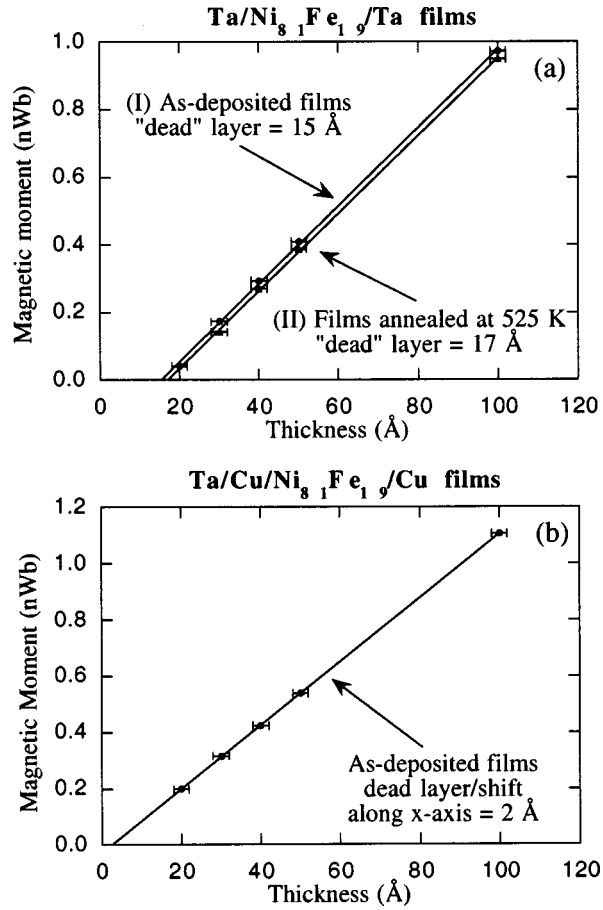

FIG. 3. (a) Total magnetic moment of $Ni_{81}Fe_{19}$ films surrounded by 5 nm Ta seed and 10 nm Ta cap layers (denoted as $Ta/Ni_{81}Fe_{19}/Ta$) as a function of the permalloy thickness. Measurements were performed on a whole 6 in. wafer using a B-H looper for (I) as-deposited films and (II) the same films annealed at 525 K for 1/2 h. 525 K temperature for this set of films was chosen to investigate the annealing temperatures close to actual processing temperatures. The data were fitted with a linear dependence. If there were no losses of moment at the interfaces, the linear dependence of the moment as a function of thickness would start at the origin (0,0) of the graph. From an intercept of the straight line with the thickness axis, the loss of moment can be expressed in terms of an equivalent magnetic dead layer of thickness (I) 1.5 ± 0.2 nm for as-deposited and (II) 1.7 ± 0.2 nm for annealed films. Notice that upon annealing at 525 K the moment decreases by approximately 20 μWb which corresponds to a 0.2 nm increase in terms of a magnetic dead layer. Both Ta interfaces contribute to the magnetic dead layer, see text. (b) The total magnetic moment of $Ni_{81}Fe_{19}$ film surrounded by 5 nm Ta/5 nm Cu seed and 10 nm Cu cap layers (denoted as $Ta/Cu/Ni_{81}Fe_{19}/Cu$) as a function of the permalloy thickness measured on whole 6 in. wafers using a B-H looper. Ta is still used as a seed layer, but the permalloy is surrounded by Cu only. The 0.2 nm shift of the linear dependence measured along the thickness axis is within the measurement error. Error bars in magnetic moment are smaller than symbols.

interfaces with Cu and therefore there is no significant paramagnetic alloy at those interfaces.

Further, as shown in Fig. 4(a), by studying the as-deposited films in series (i), it was found that the Ta seed layer interface with the $Ni_{81}Fe_{19}$ produces a 0.6 ± 0.2 nm thick magnetic dead layer. The Ta metal in the cap series (ii), on the other hand, intermixes more readily in the as-deposited films, producing a 1.0 ± 0.2 nm thick magnetic dead layer, see Fig. 4(b). Since Ta surface free energy (3.15 J/m^2) is higher than that of Ni (2.45 J/m^3),[3] it is not surpris-

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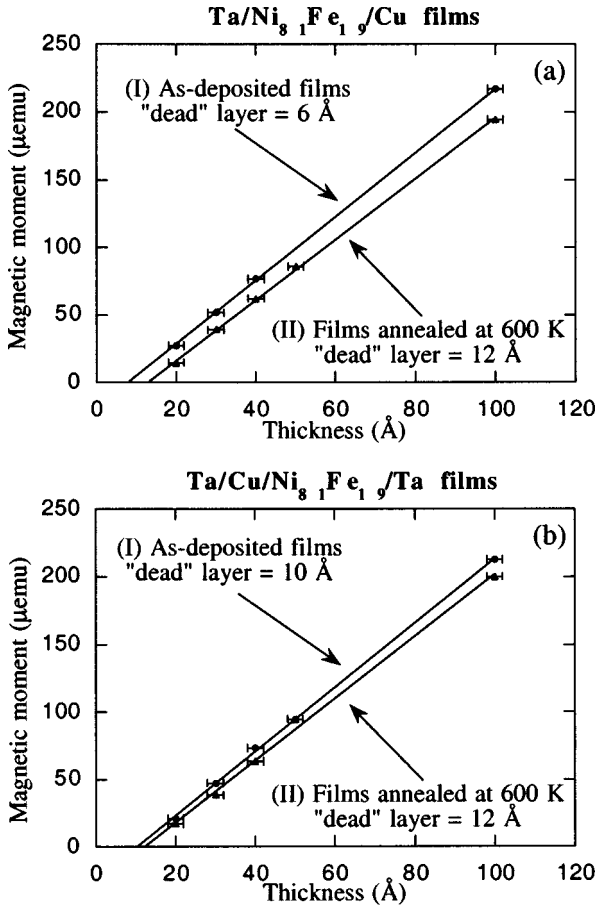

FIG. 4. (a) The total magnetic moment of $Ni_{81}Fe_{19}$ film surrounded by 10 nm Ta seed and 10 nm Cu cap layers (denoted as Ta/$Ni_{81}Fe_{19}$/Cu) as a function of the permalloy thickness measured on a 5 mm by 6 mm piece of a wafer using a SQUID magnetometer for (I) as-deposited films and (II) the same films annealed at 600 K for 1 h. The data were fitted with a linear dependence. The loss of moment can be expressed in terms of an equivalent magnetically dead layer of thickness (I) 0.6 ± 0.2 nm for as-deposited and (II) 1.2 ± 0.2 nm for annealed films. Upon annealing to 600 K the moment decreases by approximately 11 μemu which corresponds to a 0.6 nm increase of a magnetically dead layer. Only the Ta seed layer interface contributes significantly to the magnetically dead layer. (b) The total magnetic moment of $Ni_{81}Fe_{19}$ film surrounded by 10 nm Ta/5 nm Cu seed and 10 nm Ta cap layers (denoted as Ta/Cu/$Ni_{81}Fe_{19}$/Ta) as a function of the permalloy thickness measured on a 5 mm by 6 mm piece of a wafer using a SQUID magnetometer for (I) as-deposited films and (II) the same films annealed at 600 K for 1 h. The data were fitted with a linear dependence. The loss of moment can be expressed in terms of an equivalent magnetically dead layer of (I) 1.0 ± 0.2 nm for as-deposited and (II) 1.2 ± 0.2 nm for annealed films. Notice that upon annealing to 600 K the moment decreases by approximately 3.3 μemu which corresponds to 0.2 nm increase in terms of a magnetic dead layer. Only the Ta cap layer interface contributes significantly to the magnetic dead layer. Error bars in magnetic moment are smaller than symbols.

ing that the Ta atoms in the cap layer interdiffuse into the permalloy during deposition more easily and create larger magnetically dead layer than Ta atoms which are in the seed layer. Ni atoms deposited on the seed layer do not intermix as readily with Ta atoms of higher surface free energy. Therefore the two interfaces, Ta/permalloy, with 0.6 nm dead layer, and permalloy/Ta, with 1.0 nm dead layer, are not equivalent in as-deposited films. Note that, as expected, the 1.6 ± 0.2 nm total sum of thickness from series (iii) and (iv) agrees well within experimental error with the magnetic dead layer thickness for Ta/permalloy/Ta structures of series (i) of 1.5 ± 0.2 nm for as-deposited films.

Our results for as-deposited films agree very well with the previously published studies of magnetically dead layers at the permalloy interfaces with Cu (0.4 ± 0.016 nm for both interfaces in Cu/NiFe/Cu structure[4]), Ta (1.28 ± 0.2 nm for both interfaces in Ta/NiFe/Ta and 0.78 ± 0.2 nm for Ta/NiFe/Cu structures[4]) in sputtered films. However, the authors in that paper were not able to differentiate between the effects of bottom and top permalloy interfaces on the magnetically dead layers.

As shown in Fig. 4(a), upon annealing to 600 K, thermally driven interdiffusion has a much stronger effect on the originally chemically smooth Ta(seed)/ $Ni_{81}Fe_{19}$ as-deposited interface than on chemically rough $Ni_{81}Fe_{19}$/Ta(cap) as-deposited interface, and produces a doubling of the magnetically dead layer to 1.2 ± 0.2 nm. As shown in Fig. 4(b), the chemically rougher $Ni_{81}Fe_{19}$/Ta(cap) as-deposited interface only slightly increases its magnetic dead layer thickness upon annealing to 1.2 ± 0.2 nm. Therefore, the chemically and magnetically different as-deposited interfaces of Ta(seed)/permalloy and permalloy/Ta(cap) reach comparable intermixing and magnetic dead layers upon annealing to 600 K.

Furthermore, series (i) was annealed for 1/2 h at 525 K to study the effect of a more realistic processing temperature on the Ta/permalloy and permalloy/Ta interfaces. As shown in Fig. 3(a), it was found that intermixing increases slightly from 1.5 to 1.7 ± 0.2 nm for both the seed and the cap Ta interfaces. Therefore, it is concluded that up to 525 K annealing temperature the two interfaces still maintain their difference in the level of chemical intermixing.

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