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Current density distribution in a spin valve determined through *in situ* conductance measurements

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The sheet conductances of top-pinned spin valves and single-material films were measured *in situ* as the thin-film layers were grown. The data were fit to a Boltzmann transport calculation. The electrical conductivity and electron mean free paths were determined for each material by measuring the *in situ* conductance of thick single-material films. The electron transmission probabilities were deduced for each interface from the theoretical fits to the multilayer data. From these interfacial transport parameters the ratio of current density to electric field, or effective conductivity, was calculated as a function of position for the completed spin valve. It was found that the distribution of current in the spin valve was not very sensitive to the overall amount of diffuse scattering at the interfaces. [DOI: 10.1063/1.1703842]

Spin valve devices are currently used in magnetic recording read heads for magnetic data storage applications. To function as a read head, the magnetization of the free layer of the spin valve must rotate in response to the magnetic field applied by the recording medium. This requires a low free-layer coercivity and the correct zero-field state of the free layer. The distribution of current in a spin valve affects how much magnetic field is produced by the current in the free layer of the spin valve. This magnetic field biases the free layer and must be taken into consideration for engineering spin valve devices.

Understanding and controlling interfacial properties is important to optimize spin valve magnetoresistance. Creating specular interfaces on the outer surfaces of the spin valve trilayer can increase the giant magnetoresistance (GMR).[1] Optimizing the GMR requires a knowledge of the degrees of specular and diffuse scattering at all of the interfaces.

The measured spin valves had a structure of Ta (5 nm)–$Ni_{0.8}Fe_{0.2}$ (5 nm)–$Co_{0.9}Fe_{0.1}$ (1 nm)–Cu (t_{Cu})–$Co_{0.9}Fe_{0.1}$ (2 nm)–Ru (0.6 nm)–$Co_{0.9}Fe_{0.1}$ (1.5 nm)–$Ir_{0.2}Mn_{0.8}$ (8 nm)–Ta (5 nm) where t_{Cu} equaled 2, 3, 4, 5, or 6 nm. The spin valves were sputter deposited on oxidized (100) Si substrates. The base pressure was lower than 1.3×10^{-6} Pa. The deposition rates ranged from 0.025 to 0.1 nm/s. The maximum change in resistance with field, $\Delta R/R$, ranged between 5.3% for the spin valve with a 3-nm-thick Cu spacer layer and 2.6% for the spin valve with a 6-nm-thick Cu spacer layer.

The conductance was measured with a four-probe van der Pauw technique.[2] During deposition a data point was taken every second, corresponding to 0.025–0.1 nm of growth depending on the deposition rate. The change in conductance for the deposition of a single monolayer of metal is well over the minimum sensitivity of 1.5×10^{-5} Ω^{-1} for the measurement.

The conductance measurements were fitted to a spin-independent Boltzmann transport equation (BTE) calculation.[3] While the bulk and interfacial scattering rates are spin dependent, in this letter the calculation has been simplified by averaging over the two spins. In this model an electron approaching an interface may be transmitted without being scattered, specularly reflected back with no change in momentum parallel to the interface, or diffusely scattered in a random direction. The sum of the probabilities for these outcomes must equal one, leaving two independent parameters. In addition, the probabilities of transmission and specular reflection may differ for electrons approaching an interface from the top or the bottom of a multilayer. This means that, in principle, four independent parameters are necessary to describe each interface. The number of parameters used to describe the multilayer was greatly reduced by making two assumptions. The first assumption was that electrons did not specularly reflect from metal–metal interfaces. It would be difficult to have as low a conductance as was measured if there were significant specular reflection in the interior of the spin valve. The second simplifying assumption was that the transmission probability for an electron traveling either up or down through an interface was equal. This means one parameter, transmission probability, describes each interface. In general specular surfaces on the outside of a spin valve will increase the GMR.[1] Diffuse scattering on either the outer surfaces or the interior of the spin valve will lower the GMR.

The bulk transport properties of the materials used in the spin valves were found by growing relatively thick layers and measuring the asymptotic conductivity. The data used to obtain the bulk conductivities are shown in Fig. 1. The mean free paths of the electrons in each material are proportional to the bulk conductivity of the material. A value of 9×10^{6} Ω nm^2 was taken for the proportionality constant between the electron mean free paths and the conductivities of Fe, Co, Ni, and Cu.[3,4]

The measured sheet conductance as a function of layer thickness for five different spin valves is shown in Fig. 2. The most striking feature of the data is the initial drop in conductance as CoFe is added onto Cu. This is not due to islanding of the CoFe on the Cu. If that were the case, then as the CoFe islands coalesced, the conductance loss due to

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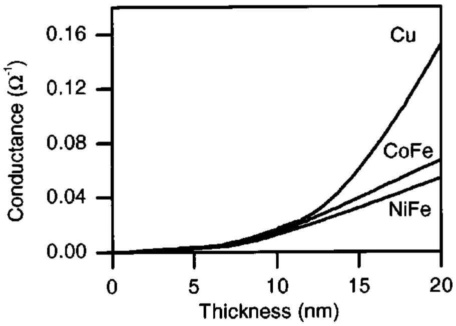

FIG. 1. Conductance as a function of thickness deposited for relatively thick layers of material. The materials are deposited with the same underlayers as are in a spin valve so that the growth conditions are the same.

TABLE I. Bulk and surface parameters used in BTE calculation.

	Conductivity $(\mu\Omega\ \mathrm{cm})^{-1}$	Mean free path	p, vacuum	T, upper	T, lower
Ta	0.007	0.4 nm	0	0	0
NiFe/Ta	0.020	1.8 nm	0	1	0
NiFe	0.045	4.0 nm	0	0.5	1
CoFe	0.046	4.1 nm	0.3	0.3	0.5
Cu1	0.080	7.2 nm	0.8	1	0.3
Cu2	0.180	16.2 nm	0.8	0.35	1
CoFe	0.056	5.0 nm	0.5	0	0.35
Ru/CoFe	0.026	1.8 nm	0	0	0
IrMn	0.010	0.8 nm	0	0	0
Ta	0.007	0.4 nm	0	0	0

islands would be regained. The conductance loss due to the CoFe-on-Cu interface remains in the completed structure. The drop in conductance is the most difficult feature in the data to explain, and the most likely to give information about the active part of the spin valve.

The drop in conductance has been attributed to inherent properties of the CoFe and Cu materials. This ignores any difference between the interface where CoFe is added onto Cu (Cu/CoFe interface) and the interface where Cu is added onto CoFe (CoFe/Cu interface). Whereas, experimental[5] and theoretical[6] studies have shown that there is more intermixing at the Cu/CoFe interface than at the CoFe/Cu interface, the drop in conductance as CoFe is added onto Cu has been seen by several groups.[3,7,8] If intermixing plays a critical role in the amount of diffuse scattering at the interfaces between CoFe and Cu, then variations in deposition conditions that change the amount of intermixing would influence the drop in conductance as CoFe is added onto Cu. Attributing the interface parameters to intrinsic material properties means that there must be the same amount of diffuse scattering at the Cu/CoFe interface as at the CoFe/Cu interface.

The drop in conductance as CoFe is added onto Cu was modeled by Bailey, Wang, and Tsymbal using a realistic band-structure calculation.[7] The advantage of that approach is that it has few adjustable parameters. However, it does not give very intuitive information about the effect of each interface on the electron transport. The Boltzmann transport model should be able to mimic the physics modeled by the realistic band-structure calculation.

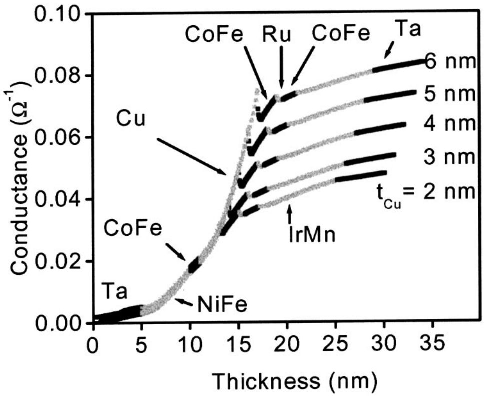

FIG. 2. Conductance as a function of the thickness measured as the films are deposited, for spin valves with varying Cu spacer layer thicknesses. The materials with the higher slopes have greater conductivities.

The drop in conductance as CoFe is added onto Cu requires that the sum of the diffuse scattering at the Cu/CoFe and CoFe/vacuum interfaces be greater than the amount of diffuse scattering at the Cu/vacuum interface. The fact that the conductance does not rise or fall as Cu is added onto CoFe indicates that the sum of the diffuse scattering at the CoFe/Cu and Cu/vacuum interfaces must be about the same as the amount of scattering at the CoFe/vacuum interface. Using these observations it is deduced that the Cu/vacuum interface is at least partially specular and that the CoFe/Cu, Cu/CoFe, and CoFe/vacuum interfaces have more diffuse scattering.

The low conductivities and short electron mean free paths of Ta and IrMn layers mean that changes in the diffuse scattering at these interfaces cause little change in conductance.[9] Therefore, the surface parameters of the Ta and IrMn interfaces are not well determined from this measurement. However, these parameters have little effect on the current in the interior active layers of the spin valve, which accounts for most of the current in the structure.

The low conductance and relatively large conductivity in the NiFe layer indicate that there is significant diffuse scattering at the NiFe interfaces. However, completely diffuse scattering on both interfaces of the NiFe layer does not lower the conductance to the values seen in the data. In order to fit the data it must be assumed that the first 2 nm of the NiFe has a lower conductivity. This is consistent with intermixing of Ta into the NiFe, creating a magnetically dead layer with a lower conductivity.[10]

The Cu layer also has a low conductance compared with its conductivity. A high amount of specular scattering at the Cu-vacuum interface is necessary to fit the drop in conductance seen as CoFe is added onto Cu. To fit the conductance while maintaining the required amount of specular scattering at the vacuum interface, the Cu was modeled with a lower conductivity in the first 2.5 nm. A possible cause for lower conductivity in the first Cu deposited is if that material were not as smooth as subsequently deposited material.[8]

The Ru is only 0.6 nm thick in these spin valves. This is not thick enough to model as a layer using the Boltzmann transport equation. Here the Ru layer is modeled as part of the CoFe layer above the Ru. The drop in conductance as Ru is added onto CoFe was modeled by dropping the metal-vacuum specularity down to zero after Ru was added and having no transmission through the CoFe/Ru interface. The conductivity of the CoFe deposited onto the Ru is lower than

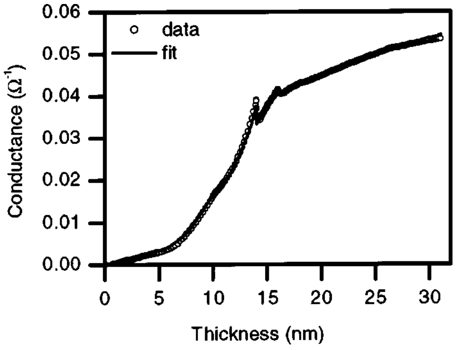

FIG. 3. Measured sheet conductance for a top-pinned spin valve with a 3-nm-thick Cu spacer layer and the calculated fit to that data.

that of the CoFe deposited onto Cu and NiFe.

Using these arguments, a set of parameters was deduced for the bulk and interfacial properties of the layers in the spin valve. These parameters are displayed in Table I. The calculated conductance as a function of the deposited thickness is plotted in Fig. 3 along with the measured conductance as a function of thickness for a spin valve with a 3 nm Cu layer. All curves in Fig. 2 are well fitted with the same set of parameters. This significantly adds assurance to the validity of the interface parameters found.

The bulk and interface parameters deduced from the measurements of conductance as a function of thickness can be used to calculate a current density in the completed multilayer. The results of this calculation are shown in Fig. 4. The decreased current density near the interfaces is due to diffuse scattering. The materials with higher conductivity have longer electron mean free paths, and the effects of their interfaces extend farther into the material. The ratio of current density to electric field is significantly lower than the bulk conductivity for the layers such as NiFe and Cu, with high bulk conductivities.

The effective conductivity was integrated over the thickness of each layer to find the fraction of the total current in that layer. To see how sensitive the fraction of total current in each layer is to changes in the interface parameters, the amount of total current in each layer was calculated for two additional cases: first, for no electron transmission through any of the metal–metal interfaces, and second, for the case where there was 100% electron transmission through each interface. The results of this calculation are shown in Fig. 5. While the conductance of the spin valve changes considerably for these different parameter sets, the fraction of the total current in each layer is not extremely sensitive to the overall amount of scattering at the interfaces of the multilayer.

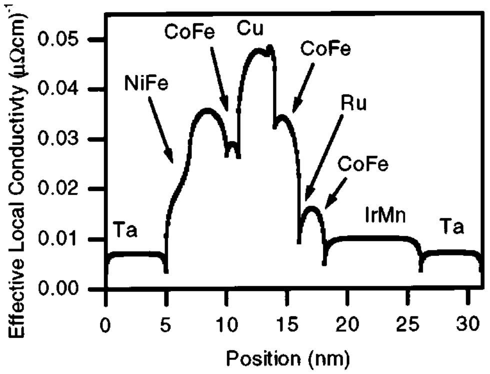

FIG. 4. Current density electric field ratio as a function of position for a completed spin valve. The effective local conductivity is much lower in the Cu layer than the bulk conductivity due to the diffuse scattering at the Cu layer interfaces.

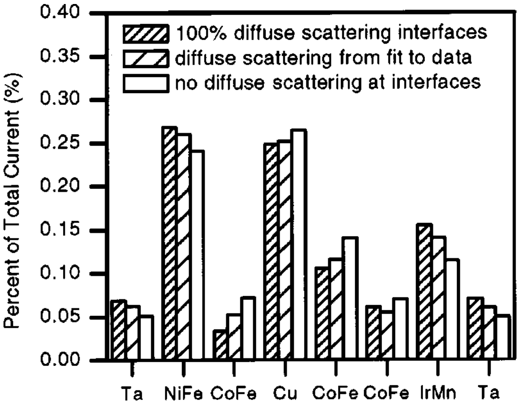

FIG. 5. The calculated percentage of the total current in a spin valve in each layer for three different sets of interface transmission probabilities. One calculation of the percentage of current in each layer is from the set of interface transmission probabilities from the fit to the conductance data. The next calculation of the relative amounts of current in each layer is from having no transmission probability at any interface in the spin valve. The third calculation of the percentage of current in each layer is from having complete transmission through each interface.

To summarize, measurements of the conductance taken as many different spin valve structures were sputter deposited showed where electron scattering occurred. This information about the scattering, in the form of transmission probabilities for the interfaces, was used to calculate the effective conductivity as a function of position in the completed spin valve. By calculating the effective conductivity for different overall amounts of scattering at the interfaces, it was found that the effective conductivity was not a strong function of the overall amount of scattering. This adds assurance that the ratio of current density to electric field calculated for the spin valve structure is accurate.

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