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Spin-flipping in Pt and at Co/Pt interfaces

H.Y.T. Nguyen, W.P. Pratt Jr., J. Bass *

Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA

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ABSTRACT

There has been recent controversy about the magnitude of spin-flipping in the heavy metal Pt, characterized by the spin-diffusion length l_{sf}^{Pt}. We propose a resolution of this controversy, and also present evidence for the importance of a phenomenon neglected in prior studies of transport across sputtered Ferromagnet/Pt (F/Pt) interfaces, spin-flipping at the interface. The latter is characterized by an interface spin-flipping parameter, $\delta_{Co/Pt}$, that specifies the probability $P=[1-\exp(-\delta)]$ of a conduction electron flipping its spin direction as it traverses a Co/Pt interface. From studies of the Current-Perpendicular-to-Plane (CPP) Resistances and Magnetoresistances of sputtered ferromagnetically coupled Co/Pt multilayers by themselves, and embedded within Py-based Double Exchange-biased Spin-Valves, we derive values at 4.2 K of $\delta_{Co/Pt}=0.9^{+0.5}_{-0.2}$, interface specific resistance, $AR^{*}_{Co/Pt}=0.74\pm 0.15$ fΩ m^2, and interface spin-scattering asymmetry, $\gamma_{Co/Pt}=0.53\pm 0.12$. This value of $\delta_{Co/Pt}$ is much larger than ones previously found for five other interfaces involving Co but not Pt. To derive δ requires knowledge of l_{sf}^{Pt} for our sputtered Pt, which we obtain from separate measurements. Combining our results with those from others, we find that l_{sf}^{Pt} for Pt is approximately proportional to the inverse resistivity, $1/\rho_{Pt}$.

1. Introduction

The large atomic number of Platinum (Pt) leads to expectation of a large spin–orbit interaction that should produce strong flipping of conduction electron spins as the electrons traverse a thin Pt layer. There has recently been controversy about the rate of spin-flipping in Pt, with values of the spin-diffusion length, l_{sf}^{Pt}, reported to range from 0.5 nm to 14 nm [1–7]. In this paper we propose an explanation for the range of values and then extend studies of spin-flipping involving Pt to Co/Pt interfaces, where we find a spin-flipping parameter, $\delta_{Co/Pt}=0.9^{+0.5}_{-0.2}$, much larger than those found for ferromagnetic/non-magnetic (F/N) or (F1/F2) interfaces involving Co but not Pt [8–12]. This large value for Co/Pt implies that a polarized current likely strongly degrades in crossing any F/Pt interface, a phenomenon neglected in prior studies of transport in F/Pt multilayers (see Ref. [13]).

Few of the authors of prior papers on l_{sf}^{Pt} intimated that the spin-diffusion length in a nominally pure metal such as Pt might not be intrinsic. But it is not. Rather, it is largely determined by the (mostly unknown) impurities and defects that scatter conduction electrons in the metal. Even at room temperature (295 K), where scattering by phonons is large, the resistivity of a sputtered metallic layer due to scattering from defects and unknown impurities is typically comparable to that due to phonons. At cryogenic temperatures, where phonon scattering is negligible, scattering from defects and unknown impurities dominates, and the spin-diffusion length is no more intrinsic than the residual resistivity. For these reasons, it is inappropriate to directly compare values of l_{sf}^{Pt} derived for samples of different purity and measured at different temperatures. In the absence of more detailed knowledge, one could try to compare values of l_{sf}^{Pt} at the same value of the resistivity (taken as a rough measure of the total scattering in the layer). Fig. 1 shows a plot of reported values of l_{sf}^{Pt} plotted against the independently measured inverse resistivity $(1/\rho_{Pt})$—or in one case (see caption) by our best estimate of this inverse resistivity as the sum of a typical residual resistivity and the expected phonon resistivity. The straight line in Fig. 1, required to pass through zero, is a least squares fit to the four data points with the largest values of $(1/\rho_{Pt})$, weighted equally (i.e., not taking account of their specified uncertainties). Fig. 1 shows that most of the data scatter roughly around this line. We take this behavior as evidence that l_{sf}^{Pt} in Pt is approximately proportional to $1/\rho_{Pt}$, and that the value of l_{sf}^{Pt} used in our present analysis below (second point from the right, see Section 2 below) is reasonable [Note: our derived value of $\delta_{Co/Pt}$ is insensitive to values of our new l_{sf}^{Pt} spanning its range of uncertainty]. Presumably the different deviations from the line indicate differences in details of impurity contents.

In Fig. 1, the four points to the right were all measured at cryogenic temperatures, whereas the six points to the left were all

* Corresponding author. Tel.: +1 517 884 5651; fax: +1 517 353 4500.
E-mail address: bass@pa.msu.edu (J. Bass).

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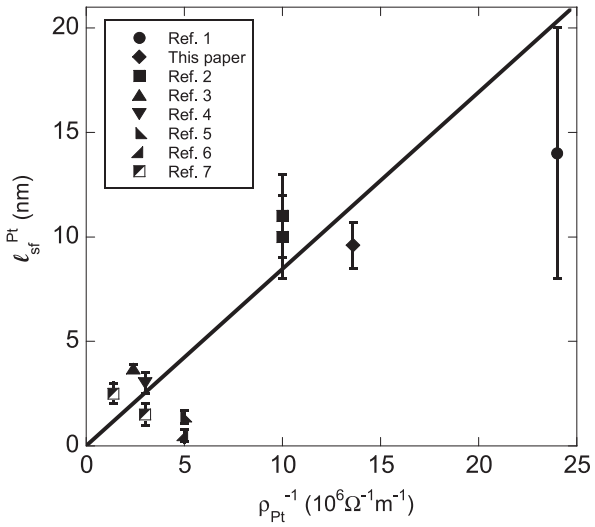

Fig. 1. l_{sf}^{Pt} vs $1/\rho_{Pt}$ for samples involving Pt. For the point from Ref. [6], we doubled the published ρ_{Pt} to correct for an omitted residual resistivity.

measured at room temperature. We take the fact that both sets of data scatter about the same line as indicating that the rate of spin-flipping due to phonon scattering, which is important at room temperature, is in the same ballpark as that due to impurity scattering, which is dominant at low temperature.

The last issue is whether l_{sf}^{Pt} in Pt might be affected by contact with an F-layer. A study by Lim et al. [14] suggests that Pt in contact with Permalloy (Py=$Ni_{0.8}Fe_{0.2}$) becomes magnetized near the Py/Pt interface over a length scale ξ increasing from about 0.2 nm at 300 K to about 0.7 nm at cryogenic temperatures. Pt as an impurity in Ni, the dominant metal in Py, stays magnetic at room temperature to concentration $x\sim0.4$ [15] and to an extrapolated $x\sim0.65$ at 4.2 K, our measuring temperature. In contrast, Pt stays magnetic in our F-metal Co to $x\sim0.9$ at room temperature and by extrapolation to still larger x at 4.2 K [15]. Roughness on the atomic scale of our sputtered Co/Pt interfaces will give Pt atoms near the interface more Co neighbors that those for Pt atoms at a perfect Co/Pt interface. We thus expect greater magnetism in Pt atoms near the interface than for Ni/Pt, and thus a larger effective ξ. It might even be that all of the Pt atoms in our thin (1.1 nm) layers are magnetized at 4.2 K, thereby strengthening the ferromagnetic coupling between Co layers that we need for our experiments below. If the magnetization within the Pt displays some disorder, it would add to any spin-flipping otherwise present at the interface. Since the ξ found for Py/Pt is comparable to the expected interface thickness in sputtered F/N multilayers ($\sim$0.6–0.8 nm) [16], it is not unreasonable to subsume any such effect into the spin-flipping due to the interface, which we do.

With this background about l_{sf}^{Pt} in hand, we now turn to our study of $\delta_{Co/Pt}$, which determines the probability of spin-flipping, $P=[1-\exp(-\delta)]$, as conduction electrons flowing perpendicular to a Co/Pt interface (Current-Perpendicular-to-Plane (CPP) geometry) cross that interface. Recently published values of $\delta_{F/N}$ or $\delta_{F1/F2}$ for sputtered Co/Cu [8], $Co_{91}Fe_9$/Cu [9], Co/Ni [10], Co/Ru [11], and Co/Ag [12] range from about 0.2 to 0.35, indicating modest spin-flipping in all five cases. In this paper we present evidence that the parameter for the sputtered Co/Pt interface, $\delta_{Co/Pt}=0.9^{+0.5}_{-0.2}$, is much larger than the other five cases, consistent with the large spin–orbit interaction expected for Pt as noted above.

Our analysis involves applying the theory of Valet and Fert (VF) [17] to resistance and magnetoresistance data on magnetic multilayers measured in the CPP geometry. For a general multilayer, the VF theory must be applied numerically, matching boundary conditions at interfaces as described in Refs. [17,18]. In the present study, we assume that the VF parameters for all metals and interfaces in our samples, except for Pt and the Co/Pt interfaces, are fixed by prior experiments made in our laboratory. Regular cross-checks, and internal consistency of repeated data sets, strongly suggest that these parameters are reproducible in our laboratory to within their specified uncertainties. We will describe below how we obtain the parameters for Pt and for Co/Pt interfaces.

2. Samples

2.1. Multilayer fabrication and structures

The CPP-MR measurements in this paper were made at 4.2 K using the crossed-superconductor technique with 150 nm thick and 1.1 mm wide superconducting Nb strips sputtered above and below the multilayer of interest [19,20]. The multilayer samples were sputtered using a system with six targets as described elsewhere [19]. With the exception of Pt, the targets and sputtering rates were the same as in previous studies of $\delta_{F/N}$ [8,12]. By the end of the last prior study with Pt, the 2.25″ diam. Pt target had become so thin at its center that we feared that the next run would burn it through. For the present study, that target was cut into three pieces, and the two thicker ones were placed one above the other in a 1″ diam. 'gun'. As the sputtering rate with the smaller target was slower ($\sim$0.19 nm/s) than that with the larger target ($\sim$0.35 nm/s), we expected the resistivity of newly sputtered 60 nm and 200 nm thick Pt films to be larger than those previously found with the larger gun. Indeed, from Van De Pauw measurements we estimate $\rho_{Pt}=75\pm10$ nΩ m, compared to 42 ± 6 nΩ m for samples sputtered with the large target [1]. Since knowing the spin-diffusion length for Pt is important for our analysis, we remeasured l_{sf}^{Pt} for the newly sputtered Pt using the same technique as in [1], obtaining $l_{sf}^{Pt}=9.6\pm1.1$ nm. The ratio 0.7 ± 0.4 of this new value to the old value of $l_{sf}^{Pt}=14\pm6$ nm overlaps with the ratio 0.6 ± 0.2 of the two Pt inverse residual resistivities, to within mutual uncertainties.

The measurements in the present paper were made on samples sputtered from two Pt pieces in the small gun as just explained. Aside from Pt, van der Pauw measurements of the resistivities of the other metals used in this study agreed to within uncertainties with prior results: Cu (present $\rho_{Cu}=6\pm1$ nΩ m vs $\rho_{Cu}=6$ nΩ m in [20] for Cu also sputtered from a large gun); Py (present $\rho_{Py}=101\pm10$ nΩ m vs $\rho_{Py}=123\pm40$ nΩ m in [12]); Co (present $\rho_{Co}=46\pm10$ nΩ m vs $\rho_{Co}=59\pm10$ nΩ m [12]). These agreements make us comfortable fixing all of the parameters other than those for Pt and Co/Pt interfaces at the values listed in [12]—except for Cu, where we now use $\rho_{Cu}=6\pm1$ nΩ m.

For Pt, we've already explained the values of ρ_{Pt} and l_{sf}^{Pt} that we use. For Co/Pt interfaces, we need to determine three parameters, the $\delta_{Co/Pt}$ that is the focus of the present paper, and the two VF parameters [17] that characterize the properties of Co/Pt interfaces. These can be chosen either as the specific resistances $AR_{Co/Pt}^{\uparrow}$ and $AR_{Co/Pt}^{\downarrow}$ (A=area through which the CPP current flows, and up and down specify that the moments of the conduction electrons are along or opposite to the magnetic moment of the F-layer through which they are passing), or as $AR_{Co/Pt}^{*}=(AR_{Co/Pt}^{\downarrow}+AR_{Co/Pt}{}^{\uparrow})/4$ and $\gamma_{CoPt}=(AR_{Co/Pt}^{\downarrow}-AR_{Co/Pt}{}^{\uparrow})/(AR_{Co/Pt}^{\downarrow}+AR_{Co/Pt}{}^{\uparrow})$. The present fits were done using $AR_{Co/Pt}{}^{\uparrow}$ and $AR_{Co/Pt}^{\downarrow}$. But we quote also the values for $AR_{Co/Pt}^{*}$ and $\gamma_{Co/Pt}$, which we compare with our previously published values [21] derived assuming $\delta_{Co/Pt}=0$. The three parameters were determined self-consistently from fits to three experimental quantities, as described below. The first experimental quantity was determined from measurements of AR vs n