Spin Injection in Mesoscopic Silver Wires: Experimental Test of Resistance Mismatch

Ryan Godfrey and Mark Johnson
Naval Research Laboratory, Washington, DC 20375, USA
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The spin polarization of current injected from a Permalloy electrode into a mesoscopic Ag wire is measured for samples with very low interface resistance. The observed value of 22.3% ± 1.6% at 79 K is an order of magnitude larger than values previously reported for low resistance interfaces and about 4 times larger than predictions of the common resistance mismatch model. These results demonstrate that high resistance barriers are not necessary for efficient spin injection.

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Basic research on the study of spin transport in nanometer sized device structures and effects related to a ferromagnetic metal (F) interface continue to be of compelling interest. As one example, there is intense theoretical [1] and experimental interest in the details of spin polarized tunneling. By utilizing the symmetry of wave functions across the barrier region, high fractional spin polarization has been reported for the current in a magnetic tunnel junction [2], and for the current injected from a ferromagnetic metal into a semiconductor [3]. While tunnel barriers are intrinsically high resistance devices, little is known about the importance of interfaces in ferromagnet/nonmagnetic material (F/N) junctions having low interface resistance. More generally, interest in spin injection and accumulation in mesoscopic metal wires has recently increased [4–6]. The focus is basic research on interfacial spin transport and details of spin scattering in the bulk of F and N, and the motivation extends to spin transport device applications [7].

A misunderstanding of effects related to different resistivities of ferromagnetic and nonmagnetic materials, often called the "resistance mismatch" [8,9] problem, has been widely cited to be a crucial factor for efficient spin injection [10] and has led to a common assumption that a tunnel barrier must be part of the F/N junction in order to achieve high spin polarization. However, this has not been experimentally and quantitatively tested. In the original theory of resistance mismatch [8,11], the interface resistance R_i and spin transmissivity η are both important. The calculation more commonly cited [9] uses the $R_i = 0$ limit of Johnson-Silsbee theory.

In this Letter, we present a systematic study of spin injection in mesoscopic Ag wires using low resistance F/N junctions for injection and detection. The resistivities of the Ag, Permalloy, and of the interface are carefully measured. An Ar ion mill is used to clean the Permalloy surface before deposition of the Ag, resulting in a low value of R_i. We measure a fractional spin polarization at 79 K that is an order of magnitude larger than values previously reported for clean interfaces [6,10]. Our highest interfacial spin polarization of $\eta = 24\%$ is as large as the largest reported for $F/I/N$ tunnel junctions, $P \approx 25\%$ [5]. Our data cannot be explained by using the common resistance mismatch model [9] and assumptions [10,12]. By fitting our results to the original Johnson-Silsbee theory, we demonstrate the importance of details of the interface, even in the low interface resistance regime, and we deduce a value of the spin diffusion length in Permalloy, $\delta_{s,f} = 14.5$ nm, 3 times longer than the previous estimate [12].

Spin polarized current driven across an $F1/N$ interface [Fig. 1(a)] supplies conduction electron spin magnetization to N at a rate $I_M = \eta_1 \mu_B I/e$, where η_1 is the fractional polarization of current crossing the interface, μ_B is the Bohr magneton, and I/e is the number current of electrons in bias current I [13]. Random spin relaxation depletes the magnetization at a rate of $1/T_2$, with T_2 the spin relaxation time. In the steady state and near the $F1/N$ interface, the nonequilibrium population of spin polarized electrons in N, often called the spin accumulation, is $\tilde{M} = I_M T_2/\mathrm{Vol}$,

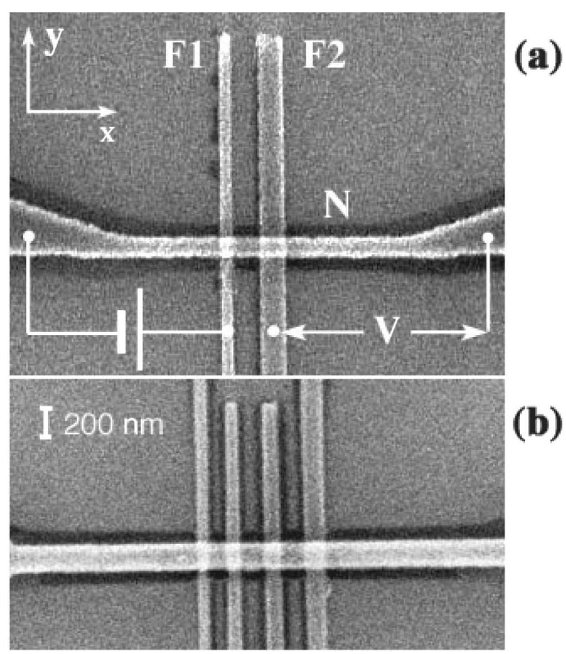

FIG. 1. Experimental geometry. Scanning electron micrograph of mesoscopic samples, with (a) an injector-detector pair and (b) an array of 4 F electrodes.

where Vol is the volume occupied by the spins. A second ferromagnetic film, $F2$, can act as a spin sensitive potentiometer and detect the spin subband electrochemical potentials associated with $\tilde{M}$. When the magnetization orientations $\vec{M}_1$ and $\vec{M}_2$ are parallel (antiparallel), the spin-dependent voltage measured by $F2$ is given by [13]

$$eV_s = +(-)\eta_2 \mu_B \tilde{M}/\chi. \tag{1}$$

Here χ is the Pauli susceptibility, η_2 is the fractional polarization of current across the $F2/N$ interface (measured when $F2$ is an injector), and the expression for eV_s represents the Zeeman energy of a spin polarized electron at the top (bottom) of the nonequilibrium population. One experimental technique for measuring $\tilde{M}$ is to record $V_s(+)$ and $V_s(-)$ by changing $\vec{M}_1$ and $\vec{M}_2$ between parallel and antiparallel. Films $F1$ and $F2$ are prepared with a uniaxial magnetization anisotropy (e.g., along $\hat{y}$), but having different coercivities, $H_{C1} \neq H_{C2}$. An external magnetic field H_y switches $\vec{M}_1$ and $\vec{M}_2$ independently.

A nonlocal geometry using a quasi-one-dimensional wire was introduced in the first spin injection experiment [13], which studied spin accumulation in bulk aluminum. This geometry recently has been used with mesoscopic, thin film metal samples [4–6]. Our nonlocal geometry is shown with the SEM of Fig. 1(a). A narrow Ag wire (N), with thickness 65 nm and width 190 nm, is fabricated on top of two Permalloy (Py) wires, $F1$ and $F2$, by thin film deposition, e-beam lithography, and lift-off. The different widths w_1 and w_2 of $F1$ and $F2$ result in different coercivities. The Py wires were e-beam deposited from a single charge of composition $Ni_{0.8}Fe_{0.2}$ in a base pressure of 1×10^{-7} torr. The top Py wire surfaces were cleaned with an Ar ion mill, using an accelerating voltage of 750 V and a current of 25 mA for 180 sec, immediately prior to deposition of the Ag. This resulted in a low interface resistance R_i which was directly measured for individual F/N junctions using a cross geometry. The value of the product of R_i and interface area is $2.4 \pm 0.6 \times 10^{-3}\ \Omega\ \mu\text{m}^2$, averaged for four interfaces at 79 K.

Referring to Fig. 1(a) and taking the $F1/N$ interface to be $x = 0$, bias current injected into N is grounded at the left end of the wire. The region of N for $x > 0$ is an equipotential surface, and the voltage measurement indicated in Fig. 1(a) would be zero if electrode $F2$ was nonmagnetic. However, the spin accumulation generated near the $F1/N$ interface diffuses equally along $\pm\hat{x}$ for a length equal to the spin diffusion length, $\delta_s \equiv \delta_{s,n} = \sqrt{DT_2}$, with D the electron diffusion constant. Electrode $F2$ measures a spin-dependent voltage V_s proportional to $\tilde{M}$. For quantitative measurements, the volume Vol occupied by the spins is $2A\delta_s$, where A is the cross sectional area of the wire and the factor 2 arises from isotropic spin diffusion along $\pm\hat{x}$ [11]. Using a free electron expression for χ and an Einstein relation, and assuming $\eta_1 = \eta_2$ for both Py interfaces, the length dependent expression for the spin transresistance $R_s = V_s/I$ is [7,14]

$$R_s = \frac{\eta^2 \rho \delta_s}{2A} e^{-L/\delta_s}. \tag{2}$$

Sample chips were mounted in a gas flow cryostat, and data were taken using an ac current bias at 35 Hz and a lock-in amplifier. An example of data taken at 79 K using in-plane field H_y is shown in Fig. 2(a). In sample P97B2b, the Ag film is 190 nm wide and the separation between injector and detector is $L = 220$ nm. The dashed trace corresponds to sweeping magnetic field H_y from -230 Oe to $+230$ Oe. The magnetizations $\vec{M}_1$ and $\vec{M}_2$ are parallel for the field ranges $H_y < 140$ Oe and $H_y > 195$ Oe, and the resistance $R \approx +R_s = 4.0\ \text{m}\Omega$ is a measure of the spin accumulation. In the field range 150 Oe $< H_y <$ 190 Oe, $\vec{M}_1$ and $\vec{M}_2$ are antiparallel, the resistance is $R \approx -R_s = -3.2\ \text{m}\Omega$, and the full amplitude of the resistance dip ΔR is twice the transresistance associated with spin accumulation, $\Delta R = 2R_s = 7.2\ \text{m}\Omega$. In the dotted trace, magnetic field is swept from $+300$ Oe to -230 Oe, and the dip occurs at $H_y < 0$ because of hysteresis. The observed values $|\pm R_s|$ are nearly symmetric about $R = 0$ and the baseline resistance R_B of about 0.4 mΩ is nearly zero because the nonlocal geometry is effective. Small differences from zero occur when the geometry deviates from ideal. When R_i is very small, current is not necessarily injected all along the F/N interface but, instead, may occur over a small region. For point injection and detection at the

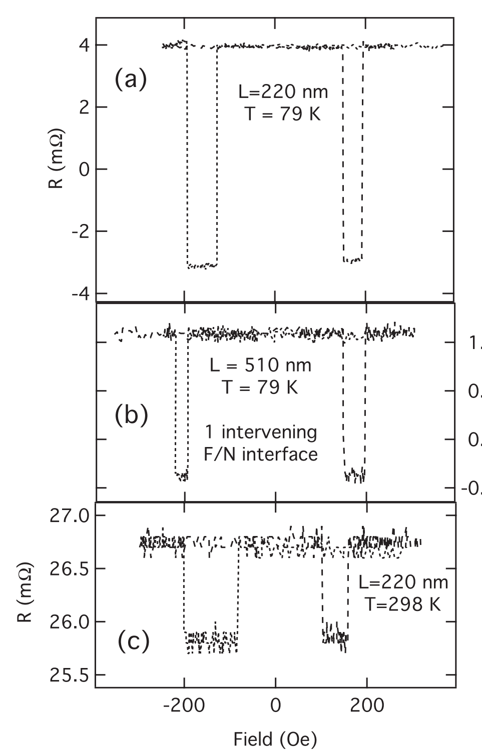

FIG. 2. Examples of data. Dashed lines: field H is swept along $\hat{y}$ from negative to positive. Dotted lines: reverse sweeps. (a), (b) Sample P97B2b. (c) Sample P97C1b.

edge (center) of the Ag wire, the value of R_B at $L = 220$ nm would be 4.4 mΩ (0.05 mΩ) [15]. From the observed value, $R_B = 0.4\,\mathrm{m}\Omega \ll 4.4\,\mathrm{m}\Omega$, we deduce that point injection is roughly midway between center and edge.

As discussed below, δ_s is sensitive to the resistivity ρ_{Ag} of the Ag, and ρ_{Ag} changes from sample to sample. To minimize this variation, samples were prepared with an array of four Py electrodes contacting each Ag wire. As seen in Fig. 1(b), the widths, and therefore coercivities, of the four F wires were uniquely different. Using these in a variety of combinations of injector and detector permitted measurements for a variety of spacings L while the variation of ρ_{Ag} was measured to be small (typically $\pm 12\%$).

In these structures, spin-dependent scattering may occur at the F/N interface of any unused F electrode within δ_s of the injector. However, such scattering is discounted as negligible for two reasons. First, an example of data taken at a long injector-detector separation, $L = 510$ nm, is shown in Fig. 2(b). Even though there is an intervening F electrode, these data show single dips in the up and down field sweeps. The baseline is flat: there is no indication of a change in resistance that would indicate a change in $\tilde{M}$ caused by the magnetization reversal of the intervening electrode. Second, we have compared data for samples taken with two F electrodes with data from samples with intervening F electrodes. For comparable Ag resistivity and separation L, the dips ΔR are the same within experimental error. We conclude that any effects of spin-dependent scattering at the N/F interface are negligible in the measurements discussed below.

Spin injection and detection in the Ag wires is robust up to room temperature, and an example of room temperature data is shown in Fig. 2(c) for sample P97C1b with $L = 220$ nm. The inset of Fig. 3 shows the nonlocal resistance for the two cases of $\vec{M}_1$ and $\vec{M}_2$ parallel (R_{par}) and antiparallel (R_{anti}) for the temperature range 79 K to 298 K. For decreasing temperature, the increase in $\Delta R = R_{\mathrm{par}} - R_{\mathrm{anti}}$ and the decrease in baseline resistance, $(R_{\mathrm{par}} + R_{\mathrm{anti}})/2$, are similar to the trends observed in Ref. [4]. Our data confirm these recent results, attributed to temperature dependent spin flip scattering in the injection process [16].

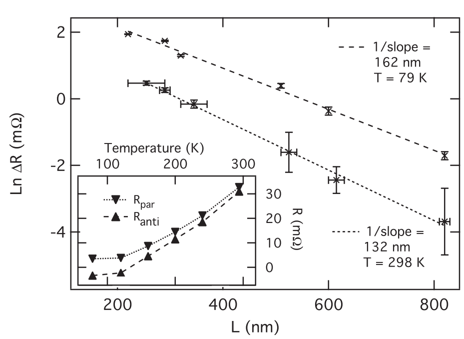

FIG. 3. Semilog plots of $\Delta R(L)$ for sample P97B2b at $T = 79$ K and 298 K, and fits. At 298 K, the relatively short spin depth causes an uncertainty in L, shown with error bars. Subsequent analyses using quasi-one- and two-dimensional models give the same results for δ_s and η'. Inset: nonlocal resistance for $L = 220$ nm, for the cases $\vec{M}_1$ and $\vec{M}_2$ parallel and antiparallel, 79 K $< T <$ 298 K.

For a given device set, the amplitude of R_s as a function of L, measured from $\Delta R(L)$, is fit to Eq. (2) to find the spin diffusion length, δ_s. Plots of $\Delta R(L)$ for sample P97B2b at 79 K and 298 K are shown in Fig. 3 along with their fits. We report on data from 2 devices at 79 K and 298 K, and on a third device at 79 K, and analyze the data [8,13] to determine the spin transport characteristics. From the measured spin depth $\delta_s = \sqrt{DT_2}$, we use an Einstein relation $D = [e^2\rho N(E_F)]^{-1}$ and a value for $N(E_F)$ from specific heat measurements [17] to solve for T_2. For example, for P97B2b with $\delta_s = 162$ nm, we find $D = 93\ \mathrm{cm}^2/\mathrm{sec}$ and $T_2 = 2.8$ psec. The spin flip probability, $\alpha = \tau/T_2$, is calculated using a Drude time for τ deduced from ρ. Finally, Eq. (2) and the amplitude R_s are used to find the average fractional polarization η' for $F1$ and $F2$.

The charge and spin transport parameters for our samples are summarized in Table I. It is interesting to note that δ_s(79 K) has an average value of 182 nm. This is much shorter than the value δ_s(4 K) = 540 nm measured in a Cu wire [4], but much longer than δ_s(10 K) = 63 nm measured in a Au wire [6]. The spin flip probability α_{Ag} at 79 K had an average value of $\alpha_{\mathrm{Ag}} = 0.0047$, roughly comparable with the value $\alpha_{\mathrm{Au}} = 0.002$ measured in a two-dimensional Au film at 77 K [14,18], but much larger than the value $\alpha_{\mathrm{Cu}} = 0.0007$ measured in Cu [4]. In samples P97B2b and P97B1b, δ_s is diminished by roughly 20% as T is increased from 79 K to 298 K. However, $1/\rho$ and D also decrease, and neither T_2 nor α_{Ag} change in the same proportion.

The most interesting result is that the value of η' for three samples at 79 K is relatively large, $22.3 \pm 1.6\%$. This is *an order of magnitude larger* than other values reported for clean F/N interfaces, 3% for F/Au [6] and 2% for F/Cu [10], larger even than values reported for F/N junctions that incorporate a low transmission tunnel barrier, 5% to 12% [4,7]. Indeed, it is approximately the same as the largest polarization reported for a $F/I/N$ junction, 25% for $F/Al_2O_3/Al$ at 4 K [5].

In the original "resistance mismatch" calculation of Johnson and Silsbee [8], charge and spin transport across a F/N interface are characterized by the average fractional

TABLE I. Characteristic parameters for several samples.

Sample	T K	ρ $\mu\Omega$ cm	δ_s nm	T_2 ps	$\alpha = \tau/T_2$	η' %
C1b	79	3.5	195	3.5	0.0043	21 ± 1
B2b	79	4.0	162	2.8	0.0054	24
B2b	298	5.5	132	2.6	0.0043	12
B1b	79	3.8	189	3.6	0.0044	22
B1b	298	4.9	152	3.0	0.0040	12

polarization p_f of current in F, the interface spin polarization efficiency η (which may include interface spin selectivity), the resistances r_f and r_n of a length of material equal to a spin diffusion length in F and N, and the intrinsic interface resistance R_i. In the limit $R_i \rightarrow 0$, the fractional spin polarization of injected current is reduced from the bulk value p_f by the factor $[1 + (r_n/r_f)(1 - p_f^2)]^{-1}$ [8]. Recently, the $R_i \rightarrow 0$ limit has been implicitly assumed and the ratio r_n/r_f has been asserted to control interfacial spin transport [9].

To test this quantitatively, we measure $\rho_f = 23.6\ \mu\Omega$ cm at 79 K as an average of five Py test strips. Using a commonly accepted value, $\delta_{s,f} = 4.3$ nm, from a previous spin valve experiment and a fit to Valet-Fert theory [12], and the area of the F/N interface (for a median width $w_f = 90$ nm), the value $r_f = 59$ mΩ is found. For sample P97B1b, for example, we have $\delta_s = 189$ nm, $\rho_n = 3.8\ \mu\Omega$ cm, and then $r_n = 600$ mΩ. Finally, the bulk spin polarization p_f of Py is taken to be 0.50 [19]. Using these values, the common model [9] predicts an injected polarization of 5.8%. Our measured value is about 4 times larger, and the common resistance mismatch model and assumptions [12] cannot be valid.

From Johnson-Silsbee theory, a general form for the interfacial magnetization current J_M includes both R_i and η [8,11]:

$$\frac{J_M}{(\mu_B J_q/e)} = \eta\left[\frac{1 + (1/R_i)(p_f/\eta)r_f(1 - \eta^2)/(1 - p_f^2)}{1 + (1/R_i)(1 - \eta^2)[r_n + r_f/(1 - p_f^2)]}\right] = \eta f(\eta) = \eta', \tag{3}$$

where η' is the experimentally measured parameter. The interface resistance R_i, normalized for a junction of median area of 90 nm by 190 nm, is $R_i = 140$ mΩ. In fitting our data to Eq. (3), all parameters are measured directly, with one exception. The value $\delta_{s,f}$, when inferred from current perpendicular-to-the-plane magnetoresistance measurements on 90 nm pore electroplated wires [12], is not reliable because the resistivities of the Py and Cu could not be measured. The value $\delta_{s,f} = 4.3$ nm deduced by the authors was smaller than their calculation, $\delta_{s,f} = 9.2$ nm. Allowing $\delta_{s,f}$ to vary as a fitting parameter, we find $\delta_{s,f} = 14.5$ nm gives a good fit to the data. The best fit assumes that η has neutral spin transmissivity, $\eta = p_f$. We note that our inferred value of $\delta_{s,f}$ is in better agreement with calculation (9.2 nm) than the value deduced in Ref. [12].

It is remarkable to note that even a small interface resistance, $R_i < r_f, r_n$, makes a substantial difference in the value of η'. Our fit, with $R_i = 140\ \text{m}\Omega < r_f$, gives $\eta' = 22\%$. By contrast, the $R_i = 0$ limit would give $\eta' = 15\%$ and the small interface resistance enhances η' by a factor of 1.5. Somewhat larger values of R_i would have an even larger effect. For $R_i = 10 \times r_n \approx 6\ \Omega$ (for our sample), η' is within a few percent of the maximum value given by the limit $\eta' \leq p_f = 50\%$. Thus, high impedance tunnel barriers are hardly necessary for efficient spin injection in metals. Instead, a low interface resistance can be used. By extension, an appropriately moderate interface resistance may provide efficient spin injection into semiconductors.

The high value of η' for our Py/Ag interfaces differs significantly from other experimental results. The Py electrodes in Ref. [6] were relatively wide, and the relatively large uncertainty in the injector-detector spacing can contribute a large uncertainty in the measurement of η'. The low value of η' reported in a Van der Pauw geometry [10] is likely due to several weaknesses of that experiment and analysis [20].

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