Enhanced spin signal in nonlocal devices based on a ferromagnetic CoFeAl alloy

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We systematically study the nonlocal spin signal in lateral spin valves based on CoFeAl injectors and detectors and compare the results with identically fabricated devices based on CoFe. The devices are fabricated by electron beam evaporation at room temperature. We observe a > 10-fold enhancement of the spin signal in the CoFeAl devices. We explain this increase as due to the formation of a highly spin-polarized Co_2FeAl Heusler compound with large resistivity. These results suggest that Heusler compounds are promising candidates as spin polarized electrodes in lateral spin devices for future spintronic applications. © *2011 American Institute of Physics*. [doi:10.1063/1.3635391]

The efficient injection, transport, and detection of spin polarized electrons are key elements in the development of spintronics, which is an emergent field aiming at enhancing electronics performance by taking advantage of the spin degrees of freedom. Nonlocal spin valves (NLSVs) (Refs. 1–4) comprising ferromagnetic (FM) and normal (N) electrodes provide a powerful tool to study spin transport and are increasingly used to gather information of the interface properties between FM and N, which determine the efficiency of spin injection and detection processes.[4] NLSVs have also practical applications as part of spin torque[5] and spin logic devices,[6] if large spin accumulation is attained. In NLSVs, a pure spin current is generated by an electric current I applied in the FM injector (Fig. 1(a)). The spin accumulation is then determined from a nonlocal voltage V using a detector consisting of a second ferromagnet[1,2,4] or a Hall cross.[3] Once the spin transport properties of N are known, it is possible to directly study the interface effects. For example, these devices allow for spin-resolved tunneling spectroscopy measurements[4,9] without the temperature and voltage bias constrains of classical methods,[7] and have been recently used to demonstrate improved spin injection after the formation of a native oxide in N,[10] or when inserting low-resistance MgO barriers,[11] at the FM/N interface.

Heusler alloys present a diverse range of magnetic properties, including ferromagnetic shape memory effects[12] and half metallicity.[13] The latter is supported by band structure calculations, which show that some Heusler compounds exhibit 100% spin polarization at the Fermi level.[12,13] For this reason, giant magnetoresistance (GMR) and tunnel magnetoresistance devices have been implemented with them.[14] However, annealing at temperatures higher than 300 °C, which is required to obtain an ordered crystalline Heusler phase, is incompatible with reliable device fabrication. Therefore, some studies focused on the properties of GMR devices based on CoFe compounds with added Al, and annealing at lower temperatures.[15] There, results show an increase in the overall GMR signal due to the addition of Al. Such an increase has been ascribed to an increase of the resistivity of the magnetic layers,[15] while recent nuclear magnetic resonance studies also point to the formation of a highly spin-polarized Co_2FeAl Heusler type structure on a local scale.[16] Both properties are of importance to increase the signal in NLSVs.

In the present work, we systematically compare the spin signal of NLSVs based on CoFe with added Al with that of NLSVs based on CoFe, which is used as a reference material to independently study the spin properties of these compounds. We observe that the addition of Al results in a 10-fold enhancement of the spin signal, making CoFeAl a very efficient spin injector/detector. Because of the simple room temperature deposition of CoFeAl, this compound can become relevant for spintronics application in lateral devices. We ascribe our observations to the formation of a highly resistive, highly spin-polarized CoFeAl compound, which supports the hypothesis of the formation of a Heusler structure.

We fabricated a set of each CoFeAl/Al and CoFe/Al NLSVs with electron-beam lithography and shadow mask electron-beam evaporation.[17,18] A scanning electron microscope (SEM) image of a typical device is shown in Fig. 1(a). In a first step (Fig. 1(b)), we evaporated the ferromagnetic electrodes from one side with a thickness of 15 nm, and widths of 150 nm (FM1) and 110 nm (FM2). After this, without breaking the vacuum, we deposited an aluminium strip in two steps from two sides (20 nm from each side, 40 nm total thickness, and 175 nm width) (Fig. 1(c)). For the CoFe NLSVs, we chose (Co:84, Fe:16 wt. %) because it is widely recognized as having one of the highest spin polarizations among the $3d$ ferromagnet alloys[19] while for the CoFeAl ones, we used (Co:36, Fe:45, Al:19 wt. %) as determined by energy-dispersive x-ray spectroscopy (EDX). The chosen composition of CoFeAl is near the optimum value obtained from GMR measurements.[15,16] All of the devices in the present study have the same thicknesses and widths for FM1, FM2, and Al, whereas the center to center distance d between the FMs was varied from 400 nm to 850 nm. The

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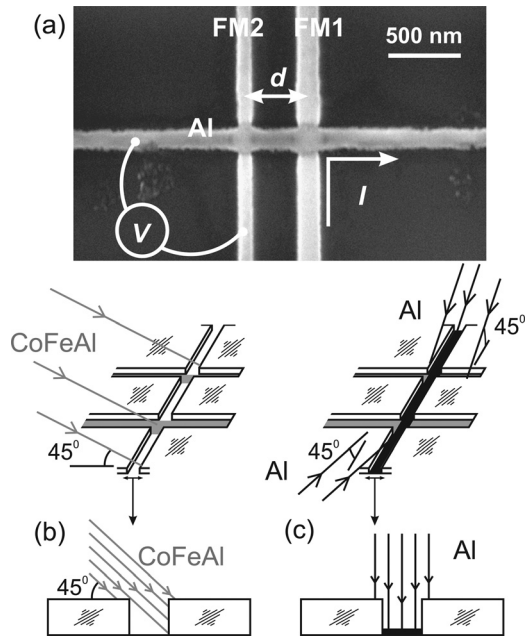b)Electronic mail: SOV@icrea.cat.

FIG. 1. (a) SEM image of a typical NLSV and measurement setup. The magnetic field, $\mu_0 H$, is applied parallel to the FMs axis. (b) Sketch of the FM electrodes evaporation and (c) the subsequent aluminium strip evaporation. The dashed regions represent the electron-beam resist.

transport measurements were done using a standard lock-in technique, injecting a current $I = 50$ μA, and measuring a voltage V at the detector (Fig. 1(a)).

Figure 2 shows typical measurements of the nonlocal spin transresistance, V/I, as a function of the magnetic field, $\mu_0 H$, for geometrically identical CoFe (red triangles) and CoFeAl (blue circles) NLSVs at $T = 77$ K and with $d = 400$ nm. The magnetic field is applied along the ferromagnetic electrodes. When it is swept from negative to positive, a change in the sign of the detector signal is observed when the magnetization of one of the electrodes reverses, and the device magnetization configuration switches from parallel to antiparallel or vice versa. Remarkably, we observe that the change in V/I, δR, is larger by more than one order of magnitude for the CoFeAl-based device, for which $\delta R \sim 12$ mΩ, when compared to the value for the CoFe-based one, where $\delta R \sim 0.78$ mΩ

(the inset of Fig. 2 shows the temperature dependence of δR, which presents an overall decrease similar to that observed in Ag devices[10]).

In order to determine the origin of the signal enhancement when using CoFeAl, we have compared δR as a function of d for the CoFeAl and CoFe set of devices (Fig. 3) and modeled the observed values using a 1D spin-dependent diffusion equation[20] solved for the NLSV geometry[21] for transparent contacts

$$\delta R = \frac{2P_{FM}^2 R_{Al}}{\left(2 + \dfrac{R_{Al}}{R_{FM}}\right)^2 e^{d/\lambda_{Al}} - \left(\dfrac{R_{Al}}{R_{FM}}\right)^2 e^{-d/\lambda_{Al}}}, \quad (1)$$

where P_{FM} is the spin polarization of the FM electrodes (CoFe or CoFeAl). R_{Al} and R_{FM} are the so-called spin resistances of the Al and FM (CoFe or CoFeAl) thin films, respectively, which are defined as $R_{Al} = 2\rho_{Al}\lambda_{Al}/S_{Al}$ and $R_{FM} = 2\rho_{FM}\lambda_{FM}/S_{FM}(1 - P_{FM}^2)$ with $\lambda_{Al,FM}$, $\rho_{Al,FM}$, and $S_{Al,FM}$ being the spin-diffusion lengths, the resistivities, and the effective cross-sectional areas of the Al strip and the FM electrodes, respectively. The assumption of transparent contacts, which is a very reasonable given the fact that we fabricate the full device structure without breaking vacuum, was verified by means of four probe resistance measurements.

As expected from Eq. (1), δR decreases nearly exponentially as a function of d with the same characteristic length λ_{Al} for the two sets of samples, which is evident in the semilogarithmic plot of Fig. 3. This proves that the signal enhancement observed in the CoFeAl devices is directly related to the ferromagnetic material and not to the spin diffusion properties of Al, thus a reliable comparison with the spin injection properties of CoFe can be done. By fitting the data to Eq. (1), we obtain P_{FM}. For this purpose, we use the resistivities $\rho_{Al} = 8 \times 10^{-8}$ Ωm, $\rho_{CoFeAl} = 4.2 \times 10^{-6}$ Ωm, and $\rho_{CoFe} = 2.3 \times 10^{-7}$ Ωm, as measured with standard four probe techniques, and the spin-diffusion lengths $\lambda_{CoFeAl} = (3.0 \pm 0.5)$ nm[15] and $\lambda_{CoFe} = (11.0 \pm 0.1)$ nm.[22] Note that the spin diffusion length of our CoFeAl films is likely overestimated and is probably smaller than 2 nm because the resistivity of our films is more than 3 times larger than that of the films in Ref. 15.
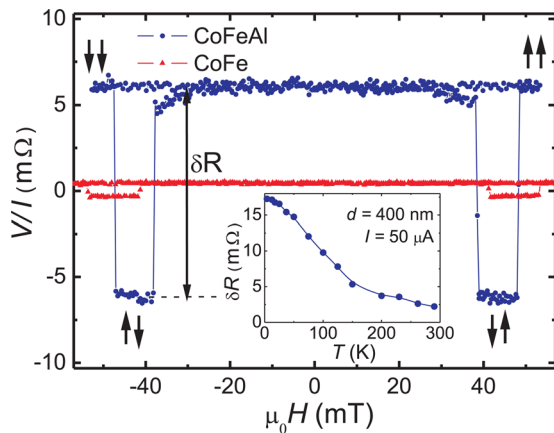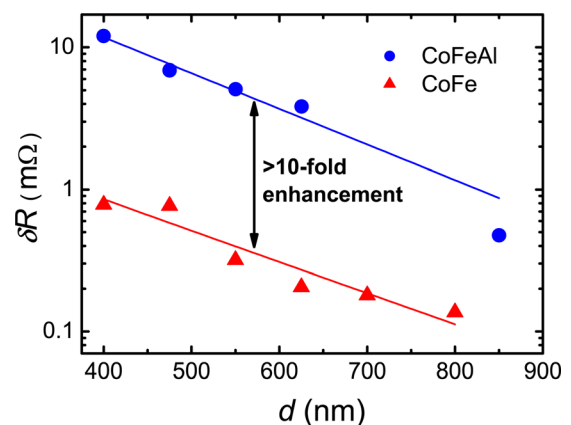

FIG. 2. (Color online) Typical nonlocal spin valve signal, V/I, as a function of $\mu_0 H$, for NLSVs based on CoFeAl (blue circles) and CoFe (red triangles) at $T = 77$ K ($I = 50$ μA and $d = 400$ nm). Inset: temperature dependence of the nonlocal spin valve transresistance change δR for a CoFeAl based NLSV ($I = 50$ μA and $d = 400$ nm).

FIG. 3. (Color online) Nonlocal spin valve resistance, δR, as a function of the distance d between the FMs at $T = 77$ K ($I = 50$ μA). The blue circles correspond to the CoFeAl based NLSVs and the red triangles to the CoFe based ones. The lines are the corresponding fittings to Eq. (1).

TABLE I. Spin injection/detection efficiency γ in metallic NLSVs.

Materials FM/N	T [K]	γ [(mΩ μ m^2)^2]	Reference
CoFeAl/Al	77	400 ± 100	This work
CoFe/Al	77	9 ± 2	This work
NiFe/Ag	77	6 ± 1	26
NiFe/Ag	79	4.0 ± 0.3	24
NiFe/Ag	77	1.34 ± 0.02	25
NiFe/Au	10	0.85 ± 0.02	23
NiFe/Cu	4.2	0.6 ± 0.1	27
Co/Cu	10	0.46 ± 0.05	23
NiFe/Cu	4.2	0.04 ± 0.01	2

The large difference between ρ_{CoFeAl} and ρ_{CoFe} highly contributes to the improved spin injection properties of CoFeAl. However, the fittings to Eq. (1) also point to an enhanced polarization with $P_{CoFe} = 0.45 \pm 0.05$ and $P_{CoFeAl} = 0.55 \pm 0.07$ for $\lambda_{CoFeAl} = 3$ nm. Given that we cannot measure P_{CoFeAl} and λ_{CoFeAl} independently with our experiments, further studies are required to probe this tendency, in particular because there exists a small overlap between the two polarizations due to their uncertainties. However, considering $\lambda_{CoFeAl} \approx 2$ nm results in $P_{CoFeAl} = 0.63 \pm 0.07$ making the difference significative.

The enhancement of the spin signal in the CoFeAl devices would thus be due to the combined effect of a resistivity and spin polarization increase, which supports the hypothesis of the local formation of a highly spin-polarized Heusler structure in this material.[16] P_{CoFe} is in agreement with previously reported values for $3d$ ferromagnetic alloys in ohmic NLSVs and is close to the spin polarization reported for CoFe in CoFe/Al$_2$O$_3$/ Al tunnel junctions,[19] validating our analysis to extract P_{FM}.

Lastly, a comparison between the achieved spin injection/ detection efficiency in our ohmic NLSVs with other values in the literature[2,23–27] can be done by defining the parameter $\gamma = (P_{FM} R_{FM} S_{FM})^2$, which is a dominant contribution in Eq. (1) and is independent of geometrical factors and the normal metal properties. The spin injection/detection efficiency is directly proportional to γ when $R_N \gg R_{FM}$, a scenario commonly found in NLSVs. This parameter is thus an important figure of merit for technological application of NLSVs. The results are summarized in Table I and show that the CoFeAl electrodes bring about a significant spin signal improvement, usually in the range of one to two orders of magnitude.

In conclusion, we have implemented CoFeAl electrodes in NLSVs. A comparative study with CoFe NLSVs shows a >10-fold enhancement of the spin signal in the CoFeAl spin valves that results from a larger resistivity and, very likely, a larger spin polarization in CoFeAl than in CoFe. The high spin polarization suggests the formation of a highly spin-polarized Heusler compound on a local scale and underscores the importance of these compounds for future spintronics

devices, where efficient spin injection using ohmic contacts is desirable to reduce dissipation. In addition, high-resistivity Heusler compounds can prove useful for spin injection into low conductance materials, such as graphene about the Dirac point, where the conductivity mismatch seriously degrades the spin injection efficiency.

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