# Current-induced magnetic switching in nanopillar spin-valve systems with double free layers

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Double soft ferromagnetic layers—CoFe/Pd/CoFe—were employed as a free layer of nanopillar spin valve. The system showed double jumps in electric resistance with respect to the spin current. Each jump corresponds to the switching of one of the CoFe layers in the double free layer. The absolute change in resistance of each jump is the same in the resistance versus current scans taken at different applied field values. While both jumps are present only in larger fields, only one jump is observed in low fields, which is attributed to the reversal of the inner CoFe layer. Furthermore, in the latter case an inversion of the hysteresis has been observed, which is explained by telegraph noise. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2714314]

## I. INTRODUCTION

Slonczewski[1] and Berger[2] predicted that a spin-polarized current transfers the spin angular momentum to the local magnetic momentum, resulting in the magnetization reversal and/or precession. This effect provides a useful technique to manipulate magnetic memory devices and tunable microwave sources.[3,4] One of the key practical issues is the reduction of the critical current density.[5,6] This study was motivated to propose an architecture to reduce the critical current density. Since the critical current density is proportional to the uniaxial (perpendicular to the plane) dipolar anisotropy,[7,8] we inserted an ultrathin Pd spacer into the middle of the free layer to introduce the interfacial perpendicular anisotropy, which in turn compensates the uniaxial dipolar anisotropy. Apart from our original expectation, the double free layers showed an uncoupled behavior evidenced by the two individual jumps in magnetoresistance with respect to the spin current. In this paper we present an experimental observation of the spin-current-induced decoupling of the double free layers.

## II. SAMPLE PREPARATION AND EXPERIMENTAL SETUP

Based on the previous studies in Co/Pd multilayer with perpendicular magnetic anisotropy,[9,10] we chose the thickness combination in the vicinity of the reorientational transition, where weak effective in-plane uniaxial anisotropy remained from the compensation between the perpendicular interfacial anisotropy and the in-plane dipolar anisotropy. Consequently, 1 nm CoFe/0.8 nm Pd/1 nm CoFe forms a free layer of the nanopillar spin-valve structure. The overall structure was $SiO_2$/Ta(5 nm)/IrMn(1 nm)/CoFe(6 nm)/Cu(6 nm)/CoFe(1 nm)/Pd(0.8 nm)/CoFe(1 nm)/Pd(0.8 nm), as shown in Fig. 1. The nanostructure was fabricated by a stencil-mask technique.[11,12] In the technique, the nanometer-sized patterns ($100\times 150\ nm^2$) were defined by electron-beam lithography, followed by ion milling and wet etching

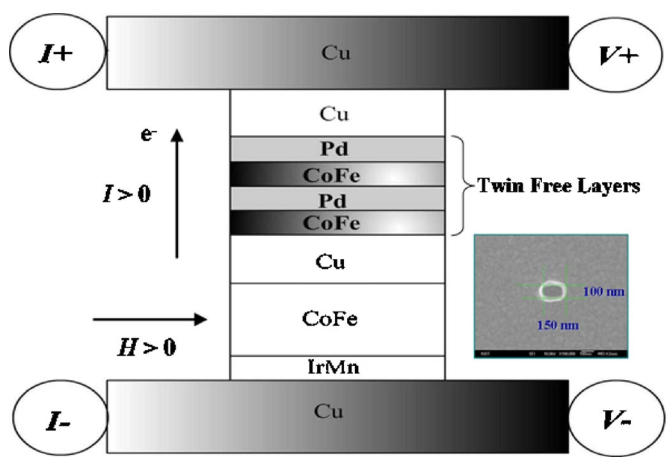


FIG. 1. Nanopillar spin-valve structure with CoFe/Pd/CoFe double free layers. The sign conventions of magnetic field and current direction are shown. Inset: SEM image of the platinum stencil mask after wet etching.

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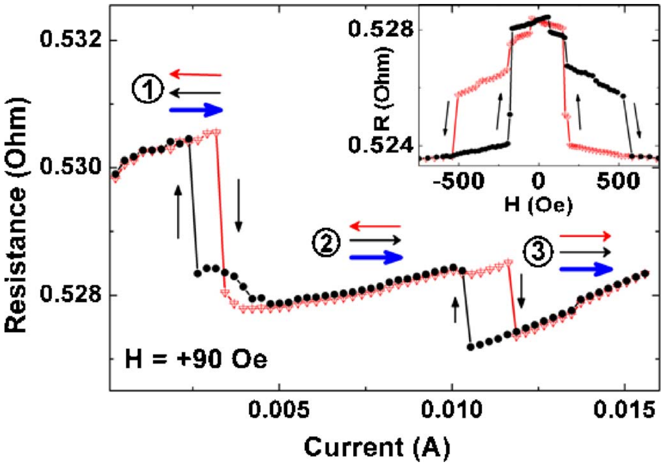


FIG. 2. Current-to-resistance $R(I)$ curve measured under a bias field 90 Oe at ambient temperature. The horizontal arrows indicate the alignment states of the fixed (lower arrow) and the two free (upper arrows) layers. Inset: Field-to-resistance $R(H)$ curve at $I=1$ mA.

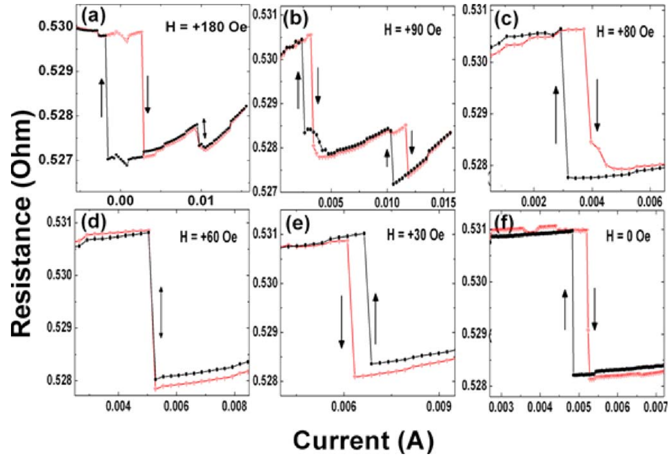


FIG. 3. Series of $R(I)$ curves measured at various external magnetic fields at ambient temperature. The arrows show the scan direction.

processes as shown in the inset. 150 nm platinum layer was used for the metal stencil. The multilayer structure was deposited through the stencil on the bottom electrode and finally, the top electrode was added.

A four-probe technique was employed to measure the field-to-resistance $R(H)$ and the current-to-resistance $R(I)$ curves. The field-to-resistance curve was measured by probing the electric resistance $R$ with sweeping the magnetic field $H$ applied along the film plane at ambient temperature. The largest resistance jump at low positive field after positive saturation actually showed two steps, which correspond to the reversals of each of double free layers. The slopes and multiple jumps at negative field resulted from the reversal of fixed layer. To avoid the current-induced effect, the current was kept constant at +1 mA. Here the positive sign was assigned for the current flowing from the free layer to the fixed layer. The current-to-resistance was measured by probing the resistance $R$ with sweeping the electric current $I$ in the range of ±30 mA with a sweeping rate 0.5 mA/s. The sample was first saturated under a magnetic field larger than 2 kOe of the opposite polarity and the measurement was done under a bias magnetic field. The strength of the bias field was chosen for initial antiparallel alignment between the fixed and free layers.

## III. RESULTS AND DISCUSSION

The sample showed double jumps in the $R(I)$ curve under a bias field range of 90–180 Oe, as plotted in Fig. 2. The resistance changes of each jump matched well those in the $R(H)$ curve shown in the inset. The double jumps came from the transitions among the three alignment states illustrated by the horizontal arrows in the figure. Note that there exists decoupled antiparallel alignment between the double free layers. It is surprising in the sense that they have been considered to be strongly coupled in continuous films.[13] However, in patterned structure the dipolar interlayer coupling prefers the antiparallel alignment, and thus, it stimulates the decoupling against the parallel exchange coupling. In contrast to this case, a strong parallel coupling generally appears in either perpendicular magnetic anisotropy systems or continuous film systems, where both the interactions prefer parallel alignment or only the parallel exchange coupling exists.[14,15]

Comparing the magnitudes of the jumps, it turned out that the inner free layer switched at a lower current than the outer free layer. It is natural since the spin transfer torque from the fixed layer was filtered out at the inner free layer, and thus, the outer layer could switch only after the switching of the inner layer. In addition to this, the inner layer felt a spin torque not only from the polarizer but also from the outer layer as well, and thus, the total torque on the inner layer was stronger than the outer one. Note that the switching of the outer layer exhibited a sizable magnetoresistance change. Such a sizable magnetoresistance might seem strange since Pd has been known as a strong spin diffuser.[16] However, since our Pd spacer was 0.8 nm, much thinner than the spin diffusion length reported of about 25 nm,[17] it is possible to have the nonvanishing spin-valve magnetoresistance.[18] This result demonstrated a possibility to manipulate the magnetic anisotropy without much destroying the magnetic transport properties with using ultrathin Pd insertion layers.

Figure 3 shows a series of $R(I)$ curves measured under various bias fields. Interestingly, the curves varied drastically with respect to the strength of the bias. The double jumps appeared under a bias larger than 90 Oe, as shown in Figs. 3(a) and 3(b), whereas a single jump was seen below 80 Oe, as shown in Figs. 3(c)–3(f). With careful comparison of the size of each jump, we concluded that the right jump—the switching of the outer free layer—disappeared at a low bias field. As shown in the inset of Fig. 2, two free layers are antiparallel at the low field region ($<80$ Oe), and they aligned to the parallel state at $\sim 90$ Oe. It is the reason of the vanishing of double jumps in the large field region.

Figures 3(d)–3(f) show the overlap ($J_C^{AP\to P}=J_C^{P\to AP}$) and inversion ($J_C^{AP\to P}<J_C^{P\to AP}$) as well as normal ($J_C^{AP\to P}>J_C^{P\to AP}$) hysteresis behaviors. Here we denote the two switching current densities as $J_C^{AP\to P}$ (antiparallel to parallel) and $J_C^{P\to AP}$ (parallel to antiparallel). In Fig. 4(a), we plot the

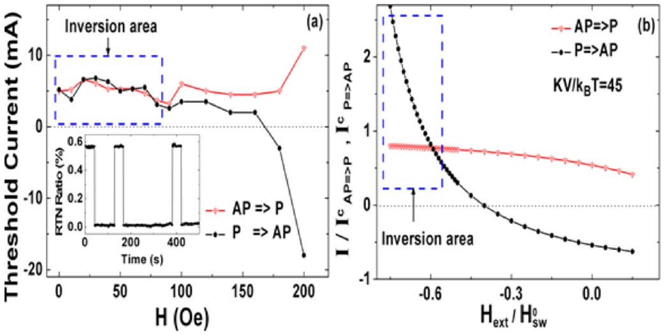


FIG. 4. (a) Critical current of the switching of the inner free layer with respect to bias field. Inset: Random telegraph noise at $H=+30$ Oe, $I=10$ mA. (b) Plot of Eqs. (1) and (2). Inversion appears in the region specified by the dashed line.

switching current versus the bias field. It was clearly seen in the figure that the inversion took place many times.

The inversion phenomenon was explained by the random telegraph noise (RTN) of bistable system.[19] The RTN behavior in our sample was confirmed by the time dependent noise measurement, as shown in the inset of Fig. 4(a). For quantitative analysis, a model consisting of the spin excitation and thermal agitation under both external magnetic field and spin current was applied to characterize the switching of the inner free layer. In the model, we defined $\tau_{\mathrm{P}}$ and $\tau_{\mathrm{AP}}$ as average dwell times of the parallel and antiparallel alignments to the fixed layer, respectively. In general $\tau_{\mathrm{P}} \neq \tau_{\mathrm{AP}}$, but RTN appeared when $\tau_{\mathrm{P}} \approx \tau_{\mathrm{AP}}$. In the modified Néel-Brown law with spin torque in the single domain model,[19] the relations between the critical current and the dwell time are given by

$$\frac{I}{I^{C}_{\mathrm{AP}\rightarrow\mathrm{P}}} = 1 - \frac{k_B T \ln(\tau_{\mathrm{P}}/\tau_0)}{KV}\left(1 - \frac{H_{\mathrm{ext}}}{H^0_{\mathrm{sw}}}\right)^{-3/2}, \quad (1)$$

$$\frac{I}{I^{C}_{\mathrm{P}\rightarrow\mathrm{AP}}} = -1 + \frac{k_B T \ln(\tau_{\mathrm{AP}}/\tau_0)}{KV}\left(1 + \frac{H_{\mathrm{ext}}}{H^0_{\mathrm{sw}}}\right)^{-3/2}, \quad (2)$$

where $\tau_0$ is an attempt time and $H_{\mathrm{sw}}$ is the switching field at zero temperature. Figure 4(b) shows the plot of equations with $\tau_0 = 10^{-9}$ s and $KV/K_BT = 45$ under the assumption of RTN condition, i.e., $\tau_{\mathrm{AP}} = \tau_{\mathrm{P}} = 1$ s. The figure shows that there exists a range of bias fields for the inversion. Note that the interlayer dipolar field was excluded in the simulation.

## IV. CONCLUSION

We observed that the spin-valve system with double free layers showed multiple hysteresis under spin current injection. The multiple switching came from the current-induced decoupling between the two free layers spaced by a 0.8 nm Pd layer. A sizable magnetoresistance effect was detected across such a thin Pd spacer. An inversion of the hysteresis loop appeared at low bias field, which was explained by the random telegraph noise based on modified Néel-Brown law.

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