Domain formation induced by perpendicular spin injection

T. Yang\textsuperscript{a,*}, A. Hirohata\textsuperscript{b}, T. Kimura\textsuperscript{a,b}, Y. Otani\textsuperscript{a,b}

\textsuperscript{a}Frontier Research System, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
\textsuperscript{b}Institute for Solid State Physics, University of Tokyo, Kashiwa, Chiba 277-8581, Japan

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Abstract

The domain formation induced by perpendicular spin injection has been studied with the magnetic nanopillar structure. When the bottom layer is an unpatterned thin film, an intermediate state is observed and characterized to be a domain formed in the bottom layer. Domain formation is also investigated when the size of the top nanomagnet is increased.

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1. Introduction

Since the theoretical prediction of the magnetic excitation induced by spin-transfer effect\cite{1,2}, the magnetization switching of a nanomagnet caused by a spin-polarized current has been extensively investigated\cite{3–6}. However, there are few reports on the domain formation in a thin film caused by a perpendicularly injected spin-polarized current. On the other hand, it is theoretically reported\cite{7} that through introducing domain structure in the nanomagnet, the switching current density could be reduced for the practical application.

In this work, we experimentally studied the spin-transfer-induced domain formation both in a thin film and in a nanomagnet.

2. Results and discussion

A nanopillar with a thick Co top nanomagnet layer and a thin unpatterned Co bottom layer is fabricated. The schematic structure is depicted in Fig. 1(a). The size of the top nanomagnet is about $140 \text{ nm} \times 70 \text{ nm}$. When a DC current is injected into the structure, the thick top layer is expected to be magnetically fixed and serve as the polarizer to produce the spin-polarized current. With this special structure, the effect of the spin-polarized current on the bottom magnetic thin film is studied.

The nanopillar is fabricated from the electron-beam-evaporated multilayers with electron-beam lithography, ion milling, and photolithography. The transport properties are measured with lock-in technique at room temperature by applying an external field along the easy axis of the nanopillar.

First, we checked the magnetization switching induced by the external field. As can be seen from Fig. 1(b), when the external field is swept between $+1500$ and $-1500 \text{ Oe}$, two resistance states can be observed in the magnetoresistance (MR) loop, corresponding to the parallel (P) and the antiparallel (AP) magnetic configurations between the two Co layers, respectively. The P-to-AP magnetization switching occurs at the small field, caused by the switching of the bottom Co thin film. The AP-to-P magnetization switching occurs at a higher field, caused by the switching of the top Co nanomagnet.

To study the influence of the spin-transfer on the bottom layer, a DC current $I_{\text{dc}}$ is injected into the nanopillar, which is preset to be the AP state, as illustrated in Fig. 1(a). In our measurement, the positive DC current is defined as flowing from the bottom to the top of the pillar. The differential resistance $\frac{dV}{dI}$ is measured by sweeping the DC current from 0 to 25 mA, then to the $-25 \text{ mA}$, and finally back to
0 mA. A hysteresis loop is observed in the $dV/dI_{dc}$ loop shown in Fig. 1(c). However, the full magnetization switching between AP and P states is not realized. When the DC current is increased from 0 mA without the external field, the AP state gradually evolves into another state, which is retained when the DC current is further increased to +25 mA and then decreased to 0 mA again. According to the resistance value at 0 mA, this state is an intermediate (IM) state between AP and P states. As the DC current is increased in the negative direction, the IM state switches back to the AP state, which is retained when the DC current is decreased back to 0 mA.

To characterize the IM state, the effect of the external field on it is investigated without the DC current. As can be seen from the evolution of the resistance with the external field (Fig. 2(a)), the IM state is switched to the P state when the field is increased to 100 Oe, coincident with the switching field of the bottom Co layer shown in Fig. 1(b). On the other hand, the IM state is transformed to the AP state when the field is increased to 1400 Oe, the same value as the switching field of the top nanomagnet shown in Fig. 1(b). The results can only be explained with the magnetic configuration sketched in Fig. 2(b) i.e., a domain in the bottom Co layer for the IM state. For such a magnetic configuration, a positive field exceeding 100 Oe aligns the whole bottom layer in the positive field direction, leading to the P state. On the other hand, a small negative field reverses the domain, resulting in the AP state. The AP state is further switched to the P state when the negative field is large enough to switch the top nanomagnet.

The formation of the domain can be explained as follows. When the positive DC current is applied to the AP state, the conduction electrons flow from the top to the bottom. When passing through the thick top layer, the electrons are spin-polarized. Through the spin-transfer effect, these spin-polarized electrons exert a torque on the magnetization of the bottom Co layer when flowing into it. The spin torque tends to align the magnetization of the bottom Co layer to be parallel to the magnetization of the top Co layer, finally forming a reversed domain in the bottom Co layer. This domain keeps stable even when the DC current is reduced to 0 mA. When the DC current is applied in the negative direction, the electrons flow from the bottom to the top. Those electrons with a spin opposite to the major spin in the top layer are reflected back into the bottom Co layer, and again exert a spin torque on the bottom Co layer, i.e., on the domain. This spin torque tends to align the magnetization of the domain to be antiparallel to the top layer. Therefore, as the DC current is increased in the negative direction, the domain is switched and hence disappears, back to the AP state again.

The above experimental results and discussions show that when a spin-polarized current is injected perpendicularly into a thin film, a domain can be formed through the spin-transfer effect. This domain is even stable when both the field and the DC current are removed. The domain formation results in an IM state.

The domain formation in the top nanomagnet is also studied by increasing its length. When the top nanomagnet...
is longer than 400 nm, a two-step switching is observed, indicating a domain formation. However, the switching current density is about $6 \times 10^7$ A/cm$^2$, not reduced compared to that through procession [3,4].

References