

## 論文の内容の要旨

### Thesis Summary

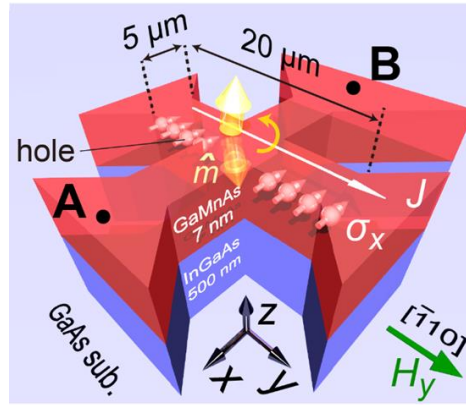
論文題目 Ultra-efficient full magnetization switching  
by spin-orbit torque in a ferromagnetic single layer

(単一強磁性層におけるスピン軌道トルクによる超高効率磁化反転)

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With the advantages of the non-volatility, rapid information process and infinite cyclability, magnetic random-access memory (MRAM) is considered as one of the most promising next-generation non-conventional memory devices that are based on the magnetic moment of the ferromagnetic materials but not on the charge storage. To improve the readability, the access latency and the energy consumption of MRAM, spin-orbit torque (SOT) is proposed to switch the magnetization using a charge current. The conventional SOT systems basically require two adjacent functional layers; a ferromagnetic layer and a non-magnetic layer with a large spin-Hall angle, which is used to generate a spin current in the non-magnetic layer and inject it into the ferromagnetic layer. Then the spin current exerts a torque on the magnetic moment and reverses it. Therefore, the switching efficiency is strongly limited by the interface quality between the two layers and the intrinsic character of the non-magnetic layer. In the typical metal systems, the critical switching current density  $J_c$  is usually larger than  $\sim 10^7 \text{ A cm}^{-2}$ . It is noticed that the SOT is contributed by two parts according to the LandauLifshitz-Gilbert (LLG) equation; damping-like torque (DLT) and field-like torque (FLT). Although the DLT helps rotate the magnetization, the large FLT hinders the full magnetization reversal by pushing the magnetization toward the in-plane direction. Hence, in the DLT-induced magnetization switching, the large FLT limits the switching efficiency and results in a large critical  $J_c$ . Therefore, to reduce  $J_c$  and to improve the switching efficiency, it is very important to achieve an interface-free SOT switching in a single layer and suppress the contribution of the FLT.

Firstly, this study is conducted in a (Ga,Mn)As single layer system with perpendicular magnetic anisotropy (PMA) to eliminate the interface limitation in the SOT magnetization switching and optimize the switching performance to achieve an ultra-high-efficient magnetization switching. As shown in Fig. 1, by injecting the charge current in the (Ga,Mn)As thin film, the induced in-plane spin component exerts a torque on the magnetic moment of the (Ga,Mn)As, which leads to the magnetization reversal just in a single layer. By combining the experimental data with calculation results, it was found that the DLT is dominant for the magnetization switching. The  $J_c$  in this work is  $3.4 \times 10^5 \text{ A cm}^{-2}$ , which is two orders of magnitude smaller than that in the conventional metal bilayer system. The low spin-scattering rate, large effective magnetic field due to the high momentum of the holes originating from impurity-band conduction, and the high spin polarization are expected in a high-quality single-crystalline GaMnAs thin film, which leads to the successful realization of the efficient full SOT switching. This work for the first time demonstrated a way to achieve full SOT switching with a very low current density using the DLT by applying a current in a single ferromagnetic layer, which provides a new method of simplifying the structure of SOT devices and offers a new possibility for dramatically increasing the switching efficiency.



**Fig.1** Schematic of SOT switching. The charge current is applied along the +y direction, and the spin component in the -x direction ( $\sigma_x$ ) exerts a torque on the magnetic moment ( $m$ ) and reverses it.

On the other hand, to further explore the detailed physical mechanism of SOT, the Oersted field and the electric field are induced to achieve the manipulation of SOT and the magnetization switching with ultralow power consumption. (Ga,Mn)As is a very interesting ferromagnetic semiconductor because the local Mn concentration has a gradient in the direction perpendicular to the film due to the segregation of Ga and Mn atoms to the surface, resulting in a nonuniform current distribution and generation of  $H_{Oe}$ , which can be utilized to suppress the

field-like term contribution and achieve an ultra-efficient magnetization switching. With carefully designing the current application direction and the thickness  $t$  of the film, the Oersted torque acts in the direction opposite to the FLT and suppresses it. When the  $t = 15$  nm, the SOT switching occurs with an extremely small value of  $J_c = 4.6 \times 10^4 \text{ A cm}^{-2}$  (the lowest value ever reported in the SOT switching until now). This work for the first time demonstrated a way to artificially control the contribution of the field-like term during SOT magnetization switching in a spin-orbit ferromagnet (Ga,Mn)As single layer by controlling the current induced Oersted field. This offers a promising technology for further increasing the switching efficiency and promoting the reduction of the energy consumption.