

博士論文（要約）

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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Firstly, this study is conducted in a (Ga,Mn)As single layer system with PMA to eliminate the interface limitation in the SOT magnetization switching and optimize the switching performance to achieve an ultra-high-efficient magnetization switching. Secondly, to further explore the detailed physical mechanisms of SOT, the Oersted field and the electric field are introduced to the material systems to achieve the manipulation of SOT and realize the magnetization switching with ultralow power consumption.

In Chapter 2, a highly efficient full SOT switching that is achieved by applying a current in a single layer of perpendicularly magnetized ferromagnetic semiconductor (Ga,Mn)As is demonstrated. In a (Ga,Mn)As thin film, due to the intrinsic bulk inversion asymmetry of its strained zinc-blende crystal structure and the structural inversion asymmetry induced by the heterostructure, intrinsic spin-orbit interactions couple the spin of a hole with its momentum and generate the effective magnetic field. The effective field is contributed by two parts, the H_D and H_R . Here, the sign and the magnitude of H_D can be changed by the state of strain. In this work, we show that the effective fields due to the spin-orbit interactions can induce a spin component whose direction depends on the current orientation and that this spin component can exert a DLT on the magnetic moment, thus enabling efficient 180 deg magnetization switching with an extremely low current density. In our high-quality single-crystalline (Ga,Mn)As thin film, we can expect a low spin-scattering rate, a large effective magnetic field due to the high momentum of the holes originating from impurity-band conduction, and a high spin polarization, leading to the successful realization of efficient full SOT switching.

In Chapter 3, a temperature T dependence and an H_{ext} dependence on the SOT switching in a (Ga,Mn)As single layer and the estimation of the heating effect are discussed. The study results show that the actual temperature during the measurement in a pure (Ga,Mn)As cross-bar is around

10 K higher than the set value. By capping the metal electrodes as heat sinks, the heating effect can be effectively eliminated. After that, with exploring the H_{ext} dependence on the SOT switching, it is found that the low H_{ext} assists the magnetization switching by decreasing the switching barrier. With the increase in the H_{ext} , the H_{ext} starts to hinder the magnetization reversal by pushing the magnetization towards the in-plane direction, resulting in an increase of the J_c .

In Chapter 4, it is demonstrated that the current-induced Oersted field (H_{Oe}) can be used to suppress the FLT contribution induced at the interface by carefully designing the current application direction and the thickness of the film. (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 non-uniform current distribution and the generation of H_{Oe} . When the current J flows in the $[\bar{1}10]$ direction, an Oersted torque ($\hat{\mathbf{t}}_{\text{Oe}}$) in the same direction as the FLT ($\hat{\mathbf{t}}_{\text{FL}}$) is induced by H_{Oe} , enhancing the field-like term contribution. In contrast, when applying J in the $[\bar{1}\bar{1}0]$ direction, $\hat{\mathbf{t}}_{\text{Oe}}$ points in the opposite direction of $\hat{\mathbf{t}}_{\text{FL}}$ and suppresses the field-like term contribution, decreasing J_c . In this work, by suppressing the field-like term contribution, the J_c is successfully decreased to as low as 4.6×10^4 A cm⁻², which is *three orders of magnitude smaller* than the J_c observed in metal bilayers. This finding paves a new promising way for exploiting the full potential of SOT devices for practical applications.

In Chapter 5, to further enhance the magnetization switching efficiency in SOT switching and realize the efficient SOT manipulation, the electric field control of the SOT switching is explored. By applying a gate voltage, the interfacial electric field and the carrier density of (Ga,Mn)As can be modulated, which promotes the successful manipulation of the SOT switching via an electrical way.

In Chapter 6, the concluding remarks and outlook are summarized. A list of publications and conferences and the acknowledgments follow Chapter 6.