Temperature dependence of the colossal spin hall effect in a BiSb(001)/MnAs bi-layer

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Recently, giant spin Hall effect (SHE) with spin Hall angle θ_{SH} larger than 1 has been observed in several topological insulators (TIs), which are exotic materials with insulating bulk states and spin-momentum locking surface states. However, since TIs are essentially insulators, their electrical conductivity σ is limited to 10^4 $\Omega^{-1}m^{-1}$, almost one order of magnitude smaller than that of typical ferromagnets used in MRAM. Recently, we have observed that BiSb can have both giant SHE (θ_{SH} ~ 52) and high σ (~2.5×10^5 $\Omega^{-1}m^{-1}$) in MnGa/BiSb(012) bi-layers at room temperature [1,2]. We also demonstrated ultra-low current magnetization switching of MnGa using SHE of BiSb(012) [1].

In this work, to explore the role of the surface states as well as the surface orientation in the generation of SHE, we have systematically investigated the spin Hall angle of BiSb(001) as a function of temperature. Inset in Fig. 1(a) shows the conduction model of BiSb, where carriers are transported through two surface states with conductivity σ_S, spin Hall angle θ_S, and total thickness t_S, and bulk states with conductivity σ_B, spin Hall angle θ_B, and total thickness t. The ratio between the surface conductance and the total conductance $\Gamma = \sigma_S t_S/(\sigma_S t_S + \sigma_B t)$ can be deduced from the temperature dependence of the conductivity of a single BiSb layer. From the temperature dependence of Γ and θ_{SH}, we can deduce the role of the surface states in the generation of θ_{SH}. We prepared a 50 nm-thick $Bi_{0.6}Sb_{0.4}$(001)/4.7 nm-thick MnAs bi-layer on GaAs(111)A substrates by molecular beam epitaxy method. The sample was patterned into a 50 μm-wide Hall bar structure by photolithography and Ar ion milling. To evaluate θ_{SH}, we used the in-plane magnetization rotation technique. Figure 1(a) shows the temperature dependence of θ_{SH} and Γ. We observe that θ_{SH} increases much faster than Γ. At room temperature, θ_{SH} is 3 but becomes as large as 166 at 8 K. In Figure 2(b), we plot the nominal sheet spin Hall angle of the whole layer $q_{SH} = \theta_{SH}/t$, and the sheet spin Hall angle of the surface states $q_S = \theta_S/t_S$ as functions of temperature. We observed almost similar trend of q_{SH} and q_S, indicating the dominance of the surface state spin Hall effect in the generation of θ_{SH}. The maximum q_S of BiSb(001) is 3.3 nm^{-1} at 8 K, which is smaller than that (q_S=5.2 nm^{-1}) of BiSb(012) at room temperature. This indicates that the surface orientation is critical for observation of colossal SHE at room temperature in BiSb. Refs. [1] N. H. D. Khang, Y. Ueda, P.N. Hai, arXiv:1709.07684. [2] Y. Ueda, N. H. D. Khang, K. Yao, and P. N. Hai, Appl. Phys. Lett. 110 (2017) 062401.

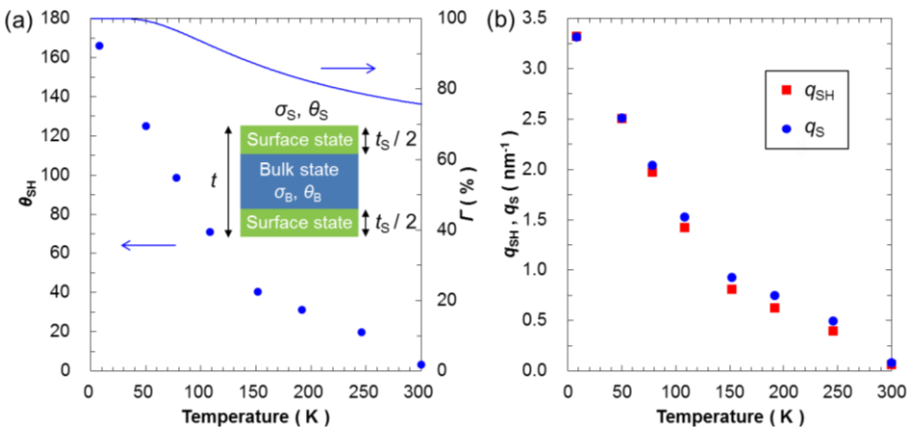

Figure 1. (a) Spin Hall angle θ_{SH} of the whole layer and the ratio Γ between the surface conductance and the total conductance as functions of temperature. Insets show the conduction model. (b) Sheet spin Hall angle of the whole layer $q_{SH} = \theta_{SH}/t$ and the surface states $q_S = \theta_S/t_S$ as functions of temperature.