

Effects of Elemental Doping and Interface Engineering on Spin-Orbit Torques in CoSi-based Topological Semimetal Thin Films

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This study reports on how Ni or Fe doping and interface engineering affect the spin-orbit torques (SOTs) generated from the topological semimetal CoSi. The CoSi films deposited on *c*-plane sapphire substrates are crystalized in a *B20* structure and textured in (210) orientation even after 15% Ni or 26% Fe doping. We characterized the SOTs from the films exerted onto the magnetization of a CoFeB layer by harmonic Hall and spin-torque ferromagnetic resonance measurements. The results show that the spin Hall efficiency ζ_{SH} of the CoSi decreases after Ni or Fe doping. According to the electrical conductivity dependence of the spin Hall conductivity, which locates at the regime of intrinsic mechanism of spin Hall effect, the reduction of ζ_{SH} may result from the degraded topological electronic structures of CoSi by the doping. It is also found that inserting a Cu layer at the Co(Ni, Fe)Si/CoFeB interface enhances the ζ_{SH} . The enhancement can be due to the improved interfacial spin transparency between the Co(Ni, Fe)Si and CoFeB layers.

Key Words— *Spin-Orbit Torques, Topological Semimetals, Elemental Doping, Interfaces*

I. INTRODUCTION

THE spin-orbit torque provides a promising method to realize ultra-fast and energy efficient writing processes in magnetoresistive random-access memories. In SOT devices, spin source materials with high charge-to-spin conversion efficiency, i.e., spin Hall efficiency ζ_{SH} , are indispensable for reliable magnetization switching and low power consumption.

Recently, topological semimetals emerged as one of the candidates for spin sources with high ζ_{SH} due to their topological band structures [1]. In our previous study, the spin Hall effect (SHE) in the topological semimetal CoSi was investigated by combining experiments and first-principles calculations [2]. It was predicted that the spin Hall conductivity (SHC) of CoSi holds a positive (negative) peak value when the Fermi level shifts down (up) to -0.16 eV (0.24 eV). By evaluation, Fermi level tuning by partially replacing the Co with Fe (26%) or Ni (15%), corresponding to hole and electron doping, could be a way to reach the peak SHCs in CoSi. Furthermore, some studies have also emphasized that the interface engineering by inserting a spacer into the NM/FM interface could intensely influence the ζ_{SH} , e.g., in the W/Cu/CoFeB, W/Cu/YIG, Pt/Cu/YIG, and Pt/Ti/CoFeB systems [3]-[5].

In this work [6], CoSi, Ni_{0.15}Co_{0.85}Si, and Fe_{0.26}Co_{0.74}Si thin films, referred as Co(Ni, Fe)Si, were deposited by co-sputtering. A *B20* structure with a (210) texture of the CoSi is preserved after the Fe or Ni doping. Harmonic Hall and spin-torque ferromagnetic resonance (ST-FMR) measurements were used to study the SOT in the Co(Ni, Fe)Si/CoFeB and Co(Ni, Fe)Si/Cu/CoFeB heterostructures. We found that the ζ_{SH} of the CoSi film decreases by Fe or Ni doping, and the ζ_{SH} of the Co(Ni, Fe)Si films is enhanced by the Cu layer insertion.

II. EXPERIMENTAL METHODS

The Co(Ni, Fe)Si films were deposited on Al₂O₃(0001) substrates by magnetron co-sputtering with four individual

targets including Co, Si, Ni, and Fe. During the deposition, the substrate temperature was 670 °C, and the process pressure was 0.32 Pa (in Ar gas). The compositions of the films were confirmed by the X-ray fluorescence. The out-of-plane XRD measurements were performed with Cu *K* α radiation ($\lambda = 0.154$ 18 nm). The Co(Ni, Fe)Si (9)/CoFeB (2) and Co(Ni, Fe)Si (9)/Cu (3)/CoFeB (2) heterostructures (thickness in nm) were microfabricated into Hall bar structures (width: 10 μm , length: 25 μm) for harmonic Hall measurements or rectangular-shape structures (width: 10 μm , length: 40 μm) for ST-FMR measurements. In the harmonic Hall measurements, the applied sinusoidal current holds a constant amplitude ~ 10 mA with a frequency ~ 133 Hz. The harmonic Hall signals were measured by a lock-in amplifier (nf LI5660). In the ST-FMR measurements, the RF power of 10 dBm was applied with a frequency $f = 6\sim 13$ GHz from a signal generator (Keysight E8257D).

III. RESULTS AND DISCUSSIONS

A. Film characterizations

The XRD patterns of the 9-nm-thick Co(Ni, Fe)Si films are shown in Fig. 1. Diffraction peaks of the (210) lattice planes of *B20*-type CoSi are observed in all the patterns, indicating the CoSi films maintain the *B20* structure after doping with 15% Ni or 26% Fe. The diffraction peaks from other lattice planes are not observed except those from the substrates, indicating the films are highly textured in the (210) orientation. The surfaces of the films are flat enough with average roughness up to ~ 0.35 nm and peak-to-valley up to ~ 3.7 nm, which are measured by atomic force microscope. The Co(Ni, Fe)Si films are confirmed to be paramagnetic at room temperature by a vibrating-sample magnetometer. The inset of the Fig. 1 shows the heterostructures used in the spin-transport measurements. The saturation magnetization of the CoFeB layer is evaluated to be 1200 emu/cm³.

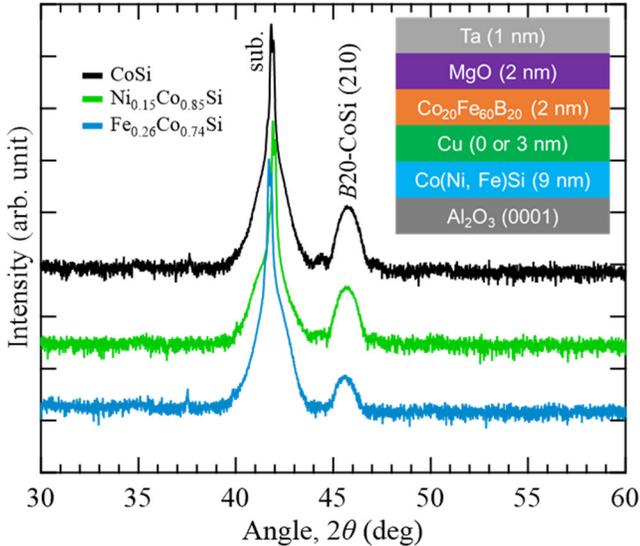


Fig. 1. XRD patterns of 9-nm-thick CoSi, $\text{Ni}_{0.15}\text{Co}_{0.85}\text{Si}$, and $\text{Fe}_{0.26}\text{Co}_{0.74}\text{Si}$ films. The inset illustrates the heterostructure used in spin-transport measurements.

B. Spin-transport properties

Table I shows the room temperature ζ_{SH} in all the Co(Ni, Fe)Si film-based devices. In the Co(Ni, Fe)Si/CoFeB structures, the ζ_{SH} of CoSi is determined to be 9.6%, and is decreased by 81% for $\text{Ni}_{0.15}\text{Co}_{0.85}\text{Si}$ and by 43% for $\text{Fe}_{0.26}\text{Co}_{0.74}\text{Si}$. Our results also show that the electrical conductivity dependence of the spin Hall conductivity can be assigned to the regime of intrinsic mechanism of the SHE, where the band structure dominates the contribution to the SHE. The previous study has suggested that the spin Hall conductivity in CoSi is mainly contributed from the $d(\text{Co})$ - $p(\text{Si})$ orbital hybridization between the nearest Co and Si atoms [2]. Ni or Fe dopants may degrade the hybridization and destroy the topological electronic band structures of CoSi, resulting in the reduction of ζ_{SH} .

It is found that the Co(Ni, Fe)Si films in the Co(Ni, Fe)Si/Cu/CoFeB structures show higher ζ_{SH} than those in the Co(Ni, Fe)Si/CoFeB structures, as shown in Table I. To confirm this conclusion, the ST-FMR measurements were furtherly performed in a thicker $\text{Ni}_{0.15}\text{Co}_{0.85}\text{Si}$ sample (15 nm) and in a $\text{Ni}_{0.05}\text{Co}_{0.95}\text{Si}$ sample with less Ni dopants. We find all results support that insertion of a 3-nm-thick Cu layer increases the ζ_{SH} . The enhancement of the ζ_{SH} by Cu insertion may be caused by the improved interfacial spin transparency. Cu is commonly used as a spacer because of its long spin diffusion length and high transparency for spins. If the sum of the spin mixing conductance at the Co(Ni, Fe)Si/Cu and Cu/CoFeB interfaces is higher than that of Co(Ni, Fe)Si/CoFeB interface, the increasing of the ζ_{SH} can happen. Such enhancements have also been reported in W/Cu/CoFeB and W/Cu/YIG systems[3]-[4].

IV. CONCLUSION

This work investigated the SOT in the Co(Ni, Fe)Si/CoFeB and Co(Ni, Fe)Si/Cu/CoFeB structures. It is found that Ni or Fe doping may degrade the topological band structure of CoSi, leading to reduction of ζ_{SH} . Furthermore, the interface engineering by a Cu insertion at the Co(Ni, Fe)Si/CoFeB

interface enhances the ζ_{SH} of Co(Ni, Fe)Si films, which may be caused by the improved spin transparency at the interfaces.

ACKNOWLEDGEMENTS

This work was partially supported by the KAKENHI (Nos. JP20K04569, JP20H00299) from the Japan Society for the Promotion of Science (JSPS), the Inter-University Cooperative Research Program of the Institute for Materials Research, Tohoku University (No. 202112-RDKGE-0015). K.T. acknowledges the National Institute for Materials Science for the provision of a NIMS Junior Research Assistantship.

TABLE I
SUMMARY OF SPIN HALL EFFICIENCY ζ_{SH}

ζ_{SH} (%)	CoSi	$\text{Ni}_{0.15}\text{Co}_{0.85}\text{Si}$	$\text{Fe}_{0.26}\text{Co}_{0.74}\text{Si}$
w/o Cu	9.61	1.85	5.51
w/ Cu	10.91	3.97	8.25

The structure with Cu represents Co(Ni, Fe)Si(9)/Cu(3)/CoFeB(2), while that without Cu represents Co(Ni, Fe)Si(9)/CoFeB(2). The Co(Ni, Fe)Si (9 nm) stacks without Cu are measured by harmonic Hall measurements, and other stacks are measured by ST-FMR measurements.

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