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Tunnel magnetoresistance effect in a magnetic tunnel junction with a B2-Fe$_3$Sn electrode

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ABSTRACT
In magnetic tunnel junctions (MTJs), the tunnel resistance varies as a function of the relative magnetic configuration of the electrode, in an effect called tunnel magnetoresistance (TMR). The material of which the electrodes are composed is of great importance, because TMR is very sensitive to the electronic states of the electrodes. Additionally, structural defects at the interface also have a significant influence on TMR. In this study, we employ B2-Fe$_3$Sn as the magnetic electrode of MTJs. The use of Fe$_3$Sn could solve the problem of lattice mismatch between Fe and MgO. However, the presence of dissimilar atoms in the electrodes or interface oxidation could be a source of defects at the interface. We find that MTJs with Fe$_3$Sn exhibit a TMR of 50% and an asymmetric bias dependence.

The applications of spintronics are extending not only into memory devices but also into microwave and neuromorphic technology. The tunnel magnetoresistance (TMR) effect is of great importance in spintronics and is the subject of much current research. The typical layer structure used in magnetic tunnel junctions (MTJs) is Fe(001)/MgO(001)/Fe(001), which allows the realization of a huge TMR ratio greater than 180% at room temperature thanks to coherent tunneling. Key to coherent tunneling in TMR is the presence of coherency and spin polarization of the $\Delta_1$ band. Recently, high performance MTJs that showed TMR ratio larger than 300% was realized by improvements of the interface and MgO barrier. Structural defects can destroy the coherency, leading to degradation of the TMR ratio and to a bias dependence. Therefore, lattice matching is a critical issue for MTJs. In the case of Fe/MgO/Fe junctions, there is a lattice mismatch of 4% between Fe and MgO, and so interface dislocations are found at the interface. One solution to this problem is the use of a barrier material with a lattice constant smaller than that of MgO. Sukegawa et al. introduced MgAl$_2$O$_4$(001) as a tunnel barrier in MTJs and reached a TMR ratio of 165% and a high $V_{\text{half}}$ at which the MTJ exhibited half of the TMR ratio at zero bias. Their study provided evidence that suppression of lattice mismatch can contribute to an improvement in TMR.

The opposite approach can also be taken, namely, the use of a ferromagnetic electrode with a lattice constant larger than that of Fe. The straightforward way to do this is by doping the Fe electrode with elements of large atomic radius. Recently, the B2-Fe$_3$Sn alloy with a lattice constant comparable to that of MgO has been developed by epitaxial growth on MgO(001) substrates. The B2 crystal structure based on a body-centered cubic (bcc) lattice has the great advantage of a band structure that has a fully spin-polarized $\Delta_1$ band like Fe. However, this approach has the disadvantage that Fe$_3$Sn contains dissimilar elements that could be a source of scattering. Thus, it is worth investigating the transport properties of MTJs incorporating B2-Fe$_3$Sn. In this study, we fabricate MTJs with Fe$_3$Sn electrodes and investigate magnetotransport at the junctions. We observe a TMR ratio of 50% at 9 K, as well as asymmetric bias dependence.
The layer structure of the MTJs was MgO(100)/MgO(20 nm)/Fe(50 nm)/MgO(tMgO nm)/Fe2Sn(5 nm)/Co(10 nm)/Au(30 nm). They were prepared by molecular beam epitaxy (MBE) in a chamber at a base pressure of 10⁻⁸ Pa. The 20 nm MgO buffer layer was grown in vacuum at 673 K on the MgO(100) substrate, which was prebaked at 1073 K. The 50 nm Fe film was grown at room temperature and then annealed at 523 K for 30 min. The MgO barrier layer was formed by evaporation of single-crystal MgO at room temperature followed by annealing at 473 K for 30 min. The 5 nm Fe2Sn layer was formed by co-deposition of Fe and Sn at 340 K followed by annealing at 473 K for 30 min. The 10 nm Co layer and the 30 nm Au capping layer were deposited by evaporation at room temperature. The crystallinity and epitaxial growth of the films were investigated by reflection high-energy electron diffraction (RHEED) and X-ray diffraction (XRD). After the MBE growth of the multilayer stack, MTJ structures with a junction area of 10 × 10 μm² were patterned by a conventional microfabrication process with photolithography and Ar ion-milling. The current–voltage (I–V) characteristics and magnetoresistance effects were measured by a dc four-probe method.

XRD measurements were conducted to confirm the lattice matching between Fe2Sn and MgO. Figure 1(a) shows the 2θ/θ profiles of Fe and Fe2Sn grown on the MgO(001) substrate. Peaks assigned to Fe(002) and to Fe2Sn(001) and Fe2Sn(002) were observed. Fe(001) was not observed, owing to the extinction rule. The lattice constants of Fe and Fe2Sn on the c axis were estimated as 0.2847 nm and 0.2984 nm, respectively. To reveal the lattice matching, in-plane XRD measurements were carried out, with the results shown in Fig. 1(b). For MgO/Fe, separate MgO(220) and Fe(200) peaks were found, indicating that their lattice parameters were different. The in-plane lattice constants of MgO(110) and Fe(100) were estimated as 0.2970 nm and 0.2885 nm, respectively. On the other hand, in the case of MgO/Fe2Sn, the MgO(220) and Fe2Sn(200) peaks were merged owing to their identical lattice constants. An additional peak was observed for MgO/Fe2Sn at 2θ = 30.04°, which was the Fe2Sn(100) superlattice peak resulting from the B2 crystal structure. This peak was absent for MgO/Fe because of the extinction rule. From these XRD profiles, we concluded that the lattice constants of B2-Fe2Sn and MgO matched very well.

To investigate the magnetotransport characteristics, we fabricated an MTJ with layer structure Fe(001)/MgO(001)/Fe2Sn(001). We also fabricated a conventional Fe/MgO/Fe junction as a control sample. The MgO thickness, tMgO, was 2.4 nm. Hereinafter, we shall refer to the Fe/MgO/Fe2Sn and Fe/MgO/Fe junctions as Fe2Sn-MTJ and Fe-MTJ, respectively. The TMR curves for the MTJs at a bias voltage of 10 mV are shown in Figs. 2(a) and 2(b). Magnetic fields were applied in the Fe(100) direction, which is the easy magnetization axis of Fe. The solid lines and dashed lines are the TMR curves at 9K and 20K, respectively. According to the Julliere’s formula,3 spin polarization of 70% for Fe/MgO was derived from TMR ratio of 197% for Fe-MTJ. It is as large as the value reported by Yuasa et al. in JAP,8, although it is less than that of 90% reported in other papers.9,22 The low spin polarization for the coherent tunneling was considered to be due to low deposition temperature of top electrodes.30 With respect to the products of resistance and area (RA), the Fe2Sn- and Fe-MTJs showed RA of 34 kΩ and 6.6 kΩ at 9K and 96 kΩ and 16 kΩ at room temperature, respectively. Since the junction resistance was strongly influenced the chemical bond at the interface, the difference of RA could be attributed to Sn atoms at the interface.22 The magnetotransport properties could be compared to the MTJ with an Co3MnSn electrode reported by Tanaka et al. because of similar crystal structure and its constitutional element.23 They measured the RA of 100 kΩ and TMR ratio of 10–40% at room temperature, which were same order with Fe2Sn-MTJ.

Figure 2(c) presents the bias dependence of the TMR ratio for the MTJs at room temperature. The TMR ratios were normalized by the value at zero bias voltage. A positive bias voltage is defined as electrons tunneling from the Fe2Sn (Fe) to the bottom Fe electrode. In particular, the TMR ratio decreased rapidly at a positive bias voltage. In Fig. 2(d), to reveal the asymmetric behavior, the ratio of the normalized TMR of the Fe2Sn-MTJ to the normalized TMR of the Fe-MTJ is plotted as a function 8 of bias voltage. At +800 mV, the ratio decreased by 90%, whereas it decreased by only 10% at -800 mV. This asymmetry means that the TMR was influenced significantly when the electrons tunneled from the Fe2Sn electrode to the Fe electrode.
To see the bias dependence in detail, we investigated the $dI/dV$ spectra. In Fig. 3, $dI/dV$ spectra in parallel (Fig. 3(a)) and antiparallel (Fig. 3(b)) magnetic configuration at room temperature for Fe$_3$Sn- and Fe-MTJs were shown. It appeared asymmetric behavior very clearly. In the negative bias, both of spectra for Fe$_3$Sn- and Fe-MTJs are very similar.

To understand these observations, several explanations can be considered. For the first, Sakuraba et al.\textsuperscript{24} reported that asymmetric $dI/dV$ spectra were observed in MTJs incorporating a Heusler alloy. They attributed the asymmetry to the gap in the density of states of the half-metallic Heusler alloy, which is not the case with B$_2$-Fe$_3$Sn.\textsuperscript{18} The second possible explanation is the presence of an additional incoherent transport path. Miao et al.\textsuperscript{25} discussed the additional incoherent transport via oxygen vacancies in the MgO barrier in Fe/MgO/Fe MTJs. However, in contrast to our results, they found that $dI/dV$ exhibited incoherent tunneling for both bias polarities. The third possibility is the asymmetry due to interface electronic states.\textsuperscript{26,27} Tuusan et al.\textsuperscript{26} reported that a very asymmetric bias dependence was observed in Pd/Fe/MgO/Fe MTJs owing to resonant interface states at the Fe/MgO interface.\textsuperscript{28} Beside, from the viewpoint of crystal structure of B$_2$-Fe$_3$Sn, interfacial defects could generate localized defect states that affect TMR.\textsuperscript{13-15} In the Fe$_3$Sn-MTJ, Sn, with a large atomic radius, was doped into the Fe electrode. Therefore, the randomness of the body-centered sites in the B$_2$ structure could be the source of the interfacial defect that causes the asymmetric bias dependence. Adding to that, we could not rule out the possibility of the oxidation at the MgO/Fe$_3$Sn interface. The bottom interface for Fe- and Fe$_3$Sn-MTJ were formed by same
fabrication process, whereas the top interface could be different due to doped dissimilar element, Sn. Similar interface oxidation effect was reported by Scheike et al., although their preparation method, which were sputtering and post oxidation, were different from ours. We also should notice the possibility of the existing of other phases of Fe-Sn alloy, though any evidences of such phase were not found by XRD measurements. Whatever the reason is, the interface states seem to be important. To find an explanations for this asymmetry, further investigations of the interface of various Fe$_3$Sn-MTJs using TEM or other techniques are needed.

We were interested in MTJs with layer structures Fe$_3$Sn/MgO/Fe$_3$Sn or Fe$_3$Sn/MgO/Fe. However, we did not succeed in observing tunnel transport in them, owing to the presence of pinholes. It seems that the bottom Fe$_3$Sn electrode caused some problems in the fabrication of the tunnel junctions.

In conclusion, we fabricated MTJs with Fe$_3$Sn electrodes, the lattice constant of which matched that of MgO perfectly. The MTJs exhibited a TMR ratio of 50% at 9 K and a very asymmetric bias dependence. Such degradation of TMR and asymmetric behavior could be attributed to the interface electronic states or interface oxidation between MgO barrier and Fe$_3$Sn electrode. Further investigation is expected to understand the tunneling in Fe$_3$Sn-MTJs.

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REFERENCES

1. S. D. Bader and S. S. P. Parkin, Annu. Rev. Condens. Matter. Phys. 1, 71 (2010).
2. S. Fusil, V. Garcia, A. Bartélémy, and M. Bibes, Annu. Rev. Condens. Matter. Phys. 44, 91 (2014).
3. A. V. Chumak, V. I. Vasyuchka, A. A. Serga, and B. Hillebrands, Nat. Phys. 11, 453 (2015).
4. S. Fukami, C. Zhang, S. DuttaGupta, A. Kurenkov, and H. Ohno, Nat. Mater. 15, 535 (2016).
5. J. Torrejon, M. Riou, F. A. Araujo, S. Tsunegi, G. Khalsa, D. Querlioz, P. Bortolotti, V. Cvos, K. Yakushii, A. Fukushima, H. Kubota, S. Yuasa, M. D. Stiles, and J. Grollier, Nature 547, 428 (2017).
6. S. Bhatti, R. Shibata, A. Hirohata, H. Ohno, S. Fukami, and S. Piramanayagam, Mater. Today 20, 530 (2017).
7. S. Yuasa and D. D. Djayaprawira, J. Phys. D: Appl. Phys. 40, R337 (2007).
8. S. Yuasa, T. Nagahama, A. Fukushima, Y. Suzuki, and K. Ando, Nat. Mater. 3, 868 (2004).
9. S. P. Parkin, C. Kaiser, A. Panchula, P. M. Rice, B. Hughes, M. Samant, and S. H. Yang, Nat. Mater. 3, 862 (2004).
10. W. H. Butler, X.-G. Zhang, T. C. Schulthess, and J. M. Maclaren, Phys. Rev. B 63, 054416 (2001).
11. J. Mathon and A. Umerski, Phys. Rev. B 63, 220403 (2001).
12. A. Sugihara, K. Yakushii, and S. Yuasa, Applied Physics Express 12, 023002 (2019).
13. E. Y. Tsybalk, O. N. Mryasov, and P. R. LeClair, J. Phys.: Condens. Matter 15, R109 (2003).
14. E. Tsybalk, B. Belashchenko, J. Velev, S. Jaswal, M. van Schilfgaarde, I. Oleynik, and D. Stewart, Prog. Mater. Sci. 52, 401 (2007).
15. J. P. Velev, M. Y. Zhuravlev, K. D. Belashchenko, S. S. Jaswal, E. Y. Tsybalk, T. Katayama, and S. Yuasa, IEEE Trans. Magn. 43, 2770 (2007).
16. H. Sukegawa, H. Xiu, T. Okhuko, T. Furubayashi, T. Nizeki, W. Wang, S. Kasai, S. Mitani, K. Inomata, and K. Hono, Appl. Phys. Lett. 96, 212505 (2010).
17. T. Schieke, H. Sukegawa, T. Furubayashi, Z. Wen, K. Inomata, T. Okhuko, K. Hono, and S. Mitani, Applied Physics Letters 105, 242407 (2014).
18. Y. Goto, M. Araki, N. Takahashi, T. Yanase, T. Shimada, M. Tsujikawa, M. Shirai, A. Kamimaki, S. Iihama, S. Mizukami, and T. Nagahama, Ipn. J. Appl. Phys. 57, 120302 (2018).
19. M. Julliere, Physics Letters A 54, 225 (1975).
20. S. Yuasa, A. Fukushima, T. Nagahama, K. Ando, and Y. Suzuki, Japanese Journal of Applied Physics 43, L588 (2004).
21. A. Spiessle, H. Saito, S. Yuasa, and R. Jansen, Phys. Rev. B 99, 224427 (2019).
22. X.-G. Zhang, W. H. Butler, and A. Bandyopadhyay, Phys. Rev. B 68, 092402 (2003).
23. M. A. Tanaka, Y. Ishikawa, Y. Wada, S. Hori, A. Murata, S. Horii, Y. Yamanishi, K. Mibu, K. Kondou, T. Ono, and S. Kasai, Journal of Applied Physics 111, 053902 (2012).
24. Y. Sakuraba, T. Miyakoshi, M. Ooane, Y. Ando, A. Sakuma, T. Miyazaki, and H. Kubota, Appl. Phys. Lett. 89, 052508 (2006).
25. G. X. Miao, Y. J. Park, J. S. Moodera, M. Seibt, G. Eilers, and M. Münzenberg, Phys. Rev. Lett. 100, 246803 (2008).
26. C. Tiusan, J. Faure-Vincent, C. Bellouard, M. Hehn, E. Jouguelet, and A. Schuhl, Phys. Rev. Lett. 93, 106602 (2004).
27. S. Honda, H. Itoh, and J. Inoue, J. Phys. D: Appl. Phys. 43, 135002 (2010).
28. O. Wunnerich, N. Papanikolaou, R. Zeller, P. H. Dederichs, V. Drchal, and J. Kudrnovsky, Phys. Rev. B 65, 064425 (2002).
29. L. Ye, M. Kang, J. Liu, F. von Cube, C. R. Wicker, T. Suzuki, C. Iozwiak, A. Bostwick, E. Rotenberg, D. C. Bell, L. Fu, R. Comin, and J. G. Checkelsky, Nature 555, 638 (2018).