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Conductance control by tunneling-barrier thickness optimizations in $Fe/Al_2O_3/MoS_2$ structure

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Abstract

We investigate electrical characteristics of Fe / Al_2O_3 / MoS_2 tunnel contact structures to inject spins into a MoS_2 thin film. We found that the currents maximum at Al_2O_3 thickness *d* of 2.5 nm, and they decrease as the decrease and increase in *d* from 2.5 nm. Also, we found that current depends on temperature in *d* < 1.5 nm, while it does not depend on temperature in *d* > 1.5 nm. These results indicate that thermionic emission beyond Schottky barrier formed in the MoS_2 surface is dominant in small-*d* devices, while the direct tunnel through Al_2O_3 barrier is dominant in large *d* devices. This suggests that the increase in *d* decreases the Schottky barrier height, which leads to high efficient spin injection into MoS_2 films.

1. Introduction

In semiconductor spintronics [1,2], new electronic devices that are difficult to realize only using charge are expected by utilizing spin degree of freedom of electron. SpinMOSFET is expected as one of the new spin electronic devices [3]. Recently, reported spinMOSFET based on Si [4] shows small MR ratio such as 0.1%, which is not enough. In transition-metal di-chalcogendies, MoS_2, spin-valley coupling prevent spin relaxation [5], which is a suitable channel material for spinMOSFET with high MR ratio rather than Si. In spinMOSFET, it is necessary to inject spin polarized current into MoS_2 using ferromagnetic metal electrodes, where conductance mismatch between them is a problem, because it reduces spin efficiency. Introducing appropriate contact resistance between ferromagnetic and MoS_2 is one of the solutions to overcome conductance mismatch [6]. Schottky barrier is formed on the MoS_2 surface and provides contact resistance, but it is difficult to control. Meanwhile, contact resistance because of inserting barrier layer can be controlled for obtaining appropriate contact resistance. The tunnel contact by inserting different thicknesses of Al_2O_3 layer between the metal and exfoliated monolayer MoS_2 films has been reported [7]. We focus on sputter method for MoS_2 deposition, which enables us a clean process in high vacuum.

In this study, we investigate the dependence of the current on the tunnel barrier thickness and temperature in Fe/ Al_2O_3/ MoS_2 tunnel contact structures to inject spins into a MoS_2 thin film, with calculation of the conduction mechanism in the electrical contact with different tunnel barrier thicknesses.

2. Experiments

We fabricated Fe (50 nm) / Al_2O_3 (thickness *d*: 0.5 - 3.0 nm) / MoS_2 structure on a SiO_2/Si substrate (Fig. 1 (a)). The Fe layer and MoS_2 layer were deposited by sputtering. Al_2O_3 film was deposited by atomic layer deposition. Fig. 1 (b) shows a cross-sectional TEM image of the Al_2O_3(2.5 nm)/MoS_2/SiO_2 structure, where nm-scale roughness is not observed.

3. Results and Discussion

Currents change exponentially when voltage is applied in the range of 0 - 1.0 V at RT (Fig. 2). Fig. 3 shows the temperature dependence of current in the range from 43 K to RT (293 K). In the thickness range of 0.5 to 1.0 nm, the current increases with an increase in temperature, which is attributable to thermionic emission. Meanwhile, the temperature dependence of the current is hardly seen at 1.5-3.0 nm, which is attributable to direct tunneling through Al_2O_3 film.

The dependence of the tunnel current on the *d* is simulated using 2D thermionic emission equation [8] and transmission probability (Fig. 4) in Al_2O_3 barrier. Schottky barrier height is estimated using model that Al_2O_3 and depletion layers are considered as a capacitance as shown in Fig. 5. Fig. 6 shows the simulation of dependence of the tunnel current on the *d*. At *d* = 2.2 nm, the current value comes to a peak, Thus, the dominant resistance of the contact changes at *d* = 2.2 nm. Therefore, it is considered that tunnel resistance is the main in the thicker than 2.2 nm, while the Schottky barrier resistance becomes conspicuous in the thin *d* region below 2 .2 nm. Fig. 7 shows the experimental result of the dependence of the tunnel current on *d*. In the *d* range of 0.5 - 2.5 nm, an increase in current was observed as the extraordinary increase in *d*. While, the decrease in the current was observed with the increase in *d* of 2.5 - 3.0 nm, which is an ordinary behavior based on the decrease in the tunnel probability in the Al_2O_3 layer as the increase in *d*, which are consistent with the simulation results shown in Fig. 6.

4. Conclusions

We introduced an Al_2O_3 barrier at the interface for injecting spin-polarized current from ferromagnetic metal to MoS_2 and overcome conductance mismatch. Appropriate contact resistance to overcome the conductance mismatch can be available by changing the Al_2O_3 film thickness. Therefore, highly-efficient spin injection into MoS_2 is expected.

References

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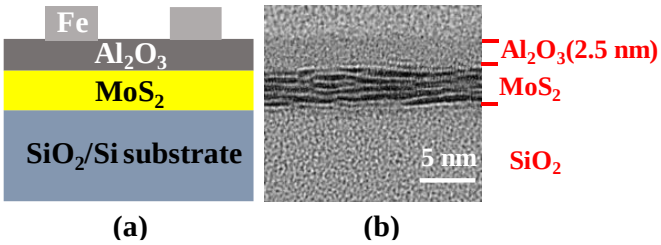

Fig. 1 (a) Schematic device structure consisting of Fe (50 nm) / Al_2O_3 (thickness *d*: 0.5 - 3.0 nm) / MoS_2. Cross-sectional TEM image (b) shows that Al_2O_3 (2.5 nm) is uniformly grown on sputtered MoS_2 with SiO_2/Si substrate.

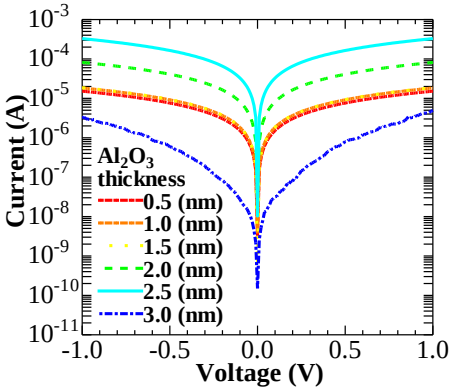

Fig. 2 I-V characteristics for various Al_2O_3 thickness. Currents exponentially change when voltages are applied in range of 0 - 1.0 V at RT.

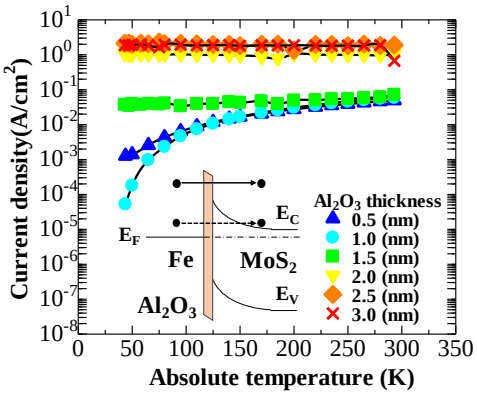

Fig. 3 Current density dependence on absolute temperature for various Al_2O_3 thickness. Thermionic emission is observed in thickness of 0.5 and 1.0 nm. Tunneling is obvsereved in thickness in the range of 1.5-3.0 nm.

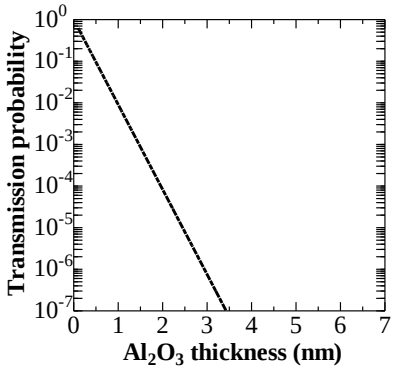

Fig. 4 Transmission probability dependece on Al_2O_3 thickness.

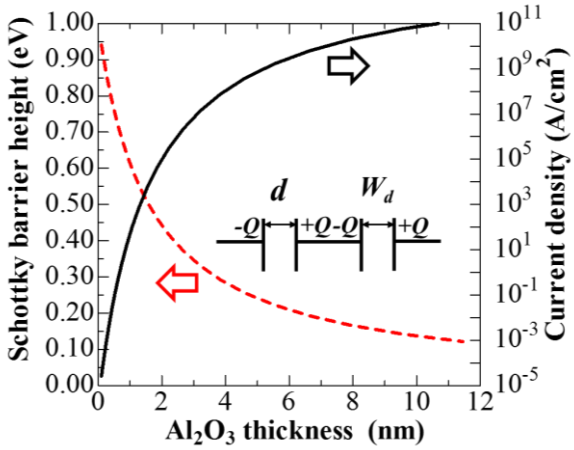

Fig. 5 Schottky barrier height and related current density dependeces on Al_2O_3 thickness. W_d is length of maximum depletion layer.

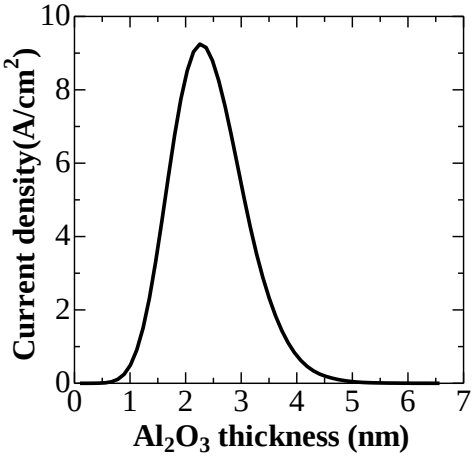

Fig. 6 Calculated current density dependeces on Al_2O_3 thickness.

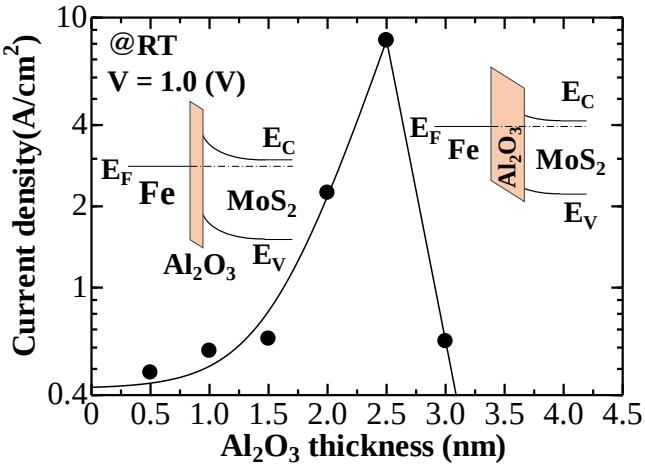

Fig. 7 Current-density dependence on Al_2O_3 thickness for Fe /Al_2O_3 (thickness *d*: 0.5 - 3.0 nm)/MoS_2 systems. Current with Al_2O_3 thickness of 2.5 nm remarkably enhanced caused by balancing between thermionic emission and tunneling current.