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Quasiparticle Tunneling Spectroscopy in Fe_4N/MgO/NbN Junctions

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1. Introduction

Spintronics has been an active research field in recent years due to their potential application in nonvolatile magnetic memories and magnetic sensors. Large negative spin polarization has been predicted theoretically in Fe_4N [1, 2]. Although Fe_4N is not a half-metal, the current spin polarization P_σ is predicted to be nearly equal 1. Band calculations show that Fe_4N has large difference between the density of state spin polarization (P_{DOS}) and P_σ. Komasaki *et al.* [3] reported negative spin polarization for Fe_4N in Fe_4N/MgO/CoFeB magnetic tunnel junctions (MTJ). However, P of Fe_4N, which was calculated from tunneling magneticresistance (TMR) using Julliere's formula, is lower than the theoretical value. In addition, P of Fe_4N decreased with decreasing MgO film thickness. These causes have not yet been clearly understood. Therefore, it is necessary to directly measure P of Fe_4N. P can be directly measured using a superconducting tunnel junction (STJ) in which one of ferromagnetic electrodes of a MTJ is replaced by a superconducting thin film. For measuring P using STJ, there are two methods: Andreev refraction (AR) and quasiparticle tunneling spectroscopy (QTS). Especially, QTS can determine positive or negative sign of P. QTS was developed by Meservey and Tedrow [4] and measured with Zeeman effect of quasiparticle by applying a magnetic field. For previous reports on measurements of P using STJs [4, 5], the superconducting Al, of which superconducting transition temperature (T_c) is approximately 2.5 K, has been frequently used as a superconducting electrode. Therefore, measurements must be carried out at low temperature, typically below 0.4 K. We make use of the superconducting NbN, of which T_c is approximately 16 K, and measurements of P using STJs could be measured at high temperature.

In this work, we report the Fe_4N/MgO/NbN STJs in which the CoFeB ferromagnetic electrode of the Fe_4N/MgO/CoFeB MTJs is replaced by the NbN superconducting electrode and P of Fe_4N using AR and QTS. The measured P of Fe_4N was compared with that in Fe_4N/MgO/CoFeB MTJs.

2. Experiments

We prepared the STJs on bared Si wafers using magnetron sputtering by the following structure: Si / buffer layer / Fe_4N(10) / Mg(0.4) / MgO(d_{MgO}) / NbN(100) (thickness in nanometer unit). For comparison, Fe_4N/MgO/CoFeB MTJs were deposited on bared Si wafers. These devices were patterned by using photolithography and Ar milling. Measurements were carried out using a four-probe method and $G - V$ curves were measured by using a lock-in amplifier.

3. Results and discussion

MgO film thickness dependence of the areal resistance (*RA*) of superconducting tunnel junctions is shown in Fig. 1. For comparison, *RA* of Fe_4N/MgO/CoFeB MTJs was displayed. *RA* of STJs was very close to that of MTJs, indicating that the qualities of the barriers for the two types of junctions were nearly identical. Normalized $G - V$ curves and the Blonder, Tinkham, and Klapwijk (BTK) fitting in STJs are shown in Fig. 2. The measurements were made at 4.2 K in zero magnetic field. The data are fit to a modified BTK theory. There are three fitting parameters: a spin polarization of the ferromagnet, a dimensionless parameter (Z) that measures the barrier strength and a superconducting gap （Δ). P of STJs with d_{MgO} = 1.00, 1.32 and 1.52 nm exhibited 0.48, 0.62 and 0.65, respectively. The estimated Δ value of STJs from our fitting was approximately 1.7 meV. These values were nearly equal to the bulk superconducting band gap of NbN of 1.67 meV. Z of STJs with d_{MgO} = 1.00, 1.32 and 1.52 nm exhibited 0.68, 2.3 and 2.5, respectively. It has been considered that the conduction mechanism of STJs is tunneling when Z is more than one. For d_{MgO} = 1.32 and 1.52 nm, Z of STJs are more than one.

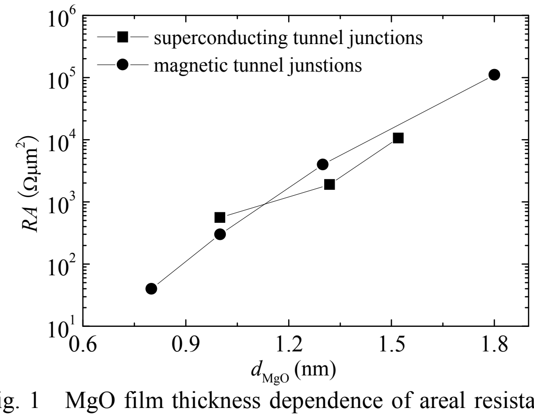

Fig. 1 MgO film thickness dependence of areal resistance (*RA*) of superconducting tunnel junctions.

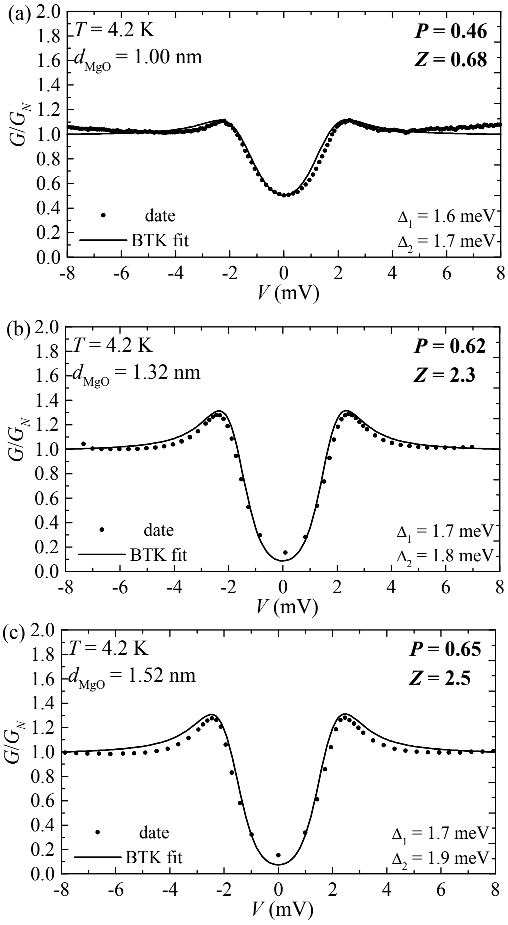

Fig. 2 Normalized $G-V$ curves and BTK fitting in superconducting tunnel junctions at 4.2 K in zero magnetic field : (a) d = 1.00 nm, (b) d = 1.32 nm and (c) d = 1.52 nm.

Therefore, the conduction mechanism of STJs with $d_{\rm MgO}$ = 1.32 and 1.52 nm is tunneling. On the other hand, the Z value of 0.68 for $d_{\rm MgO}$ = 1.0 nm may suggest that some component of metallic or Andreev conduction contributes the transport in the STJ.Normalized $G-V$ curves in superconducting tunnel junctions with $d_{\rm MgO}$ = 1.32 nm at 1.8 K and H = 0 and 5 T are shown in Fig. 3. Normalized $G-V$ curve was asymmetric due to the Zeeman splitting when magnetic field is applied. P can be calculated using the following equation:

$$P=\frac{(\sigma_4-\sigma_2)-(\sigma_1-\sigma_3)}{(\sigma_4-\sigma_2)+(\sigma_1-\sigma_3)}. \qquad (1)$$

We calculated P of STJ from equation (1), and P was -0.68±0.02. Fe_4N has a negative spin polarization.

MgO film thickness dependences of $|P|$ of Fe_4N using various methods were shown in Fig. 4. Assuming that P of CoFeB is 0.5, $|P|$ of Fe_4N is calculated from the TMR ratio. $|P|$ of Fe_4N using QTS are higher than that using TMR. $|P|$ of Fe_4N using QTS are nearly equal to the theoretical value [1, 2]. Measuring method of P using TMR is measured effective P in MTJ because TMR value could be strongly influenced for leak current and interface defection.

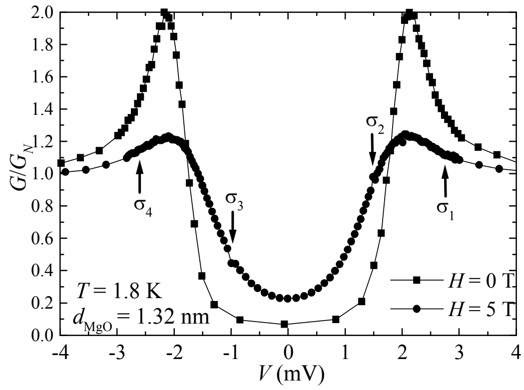

Fig. 3 Normalized $G-V$ curves in superconducting tunnel junctions with $d_{\rm MgO}$= 1.32 nm at 1.8 K and H = 0 and 5 T.

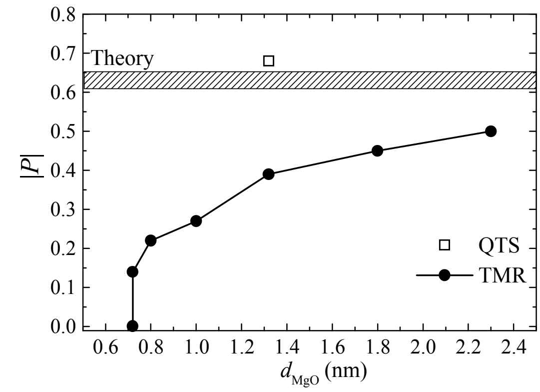

Fig. 4 MgO film thickness dependence of $|P|$ of Fe_4N using various methods.

Therefore, $|P|$ of Fe_4N using TMR is effective P in Fe_4N/MgO/CoFeB MTJs, and is lower than the theoretical value. On the other hand, QTS is directly measured polarized tunneling current using Zeeman effect of quasiparticle. It is possible to measure intrinsic P of ferromagnetic materials. From Fig. 2.(b), transport in STJ with $d_{\rm MgO}$ = 1.32 nm is tunneling conduction. We consider that $|P|$ of Fe_4N using QTS is intrinsic $|P|$ of Fe_4N.

3. Conclusions

We measured P of Fe_4N using QTS in STJs and discussed the measured P of Fe_4N in STJs compared with that in MTJs, which have the same RA. P of Fe_4N is approximately -0.68, and Fe_4N has a negative spin polarization. For the first time, we can directly measure of P of Fe_4N and decide sign of P.

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