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Magnon-assisted inelastic excitation spectra of a ferromagnetic tunnel junction

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Inelastic-electron-tunneling spectroscopy (IETS) has been applied to investigate the spin dependent tunneling process for a Ta(50 Å)/$Fe_{20}Ni_{80}$(60 Å)/IrMn(300 Å)/Co(60 Å)/Al(13 Å)-oxide/Co(40 Å)/$Fe_{20}Ni_{80}$(200 Å) spin-valve-type tunnel junction. IET spectra for both parallel and antiparallel magnetization configurations of ferromagnetic electrodes showed a strong peak at 12 mV. The subtraction spectrum defined by the difference between the spectra of both the configurations was calculated. Spin-independent inelastic excitation processes are not affected by an external magnetic field, and thus, the subtraction spectrum indicates the inelastic modes induced only by the magnetic origin. It showed a strong peak at 12 and 20 mV for the positively and negatively biased direction of the bottom electrode, respectively. The tendency of the tunneling magnetoresistance ratio to decrease with bias voltage agreed with the shape of the subtraction spectrum. By assuming the surface magnon excitation, we obtained the distributions of the correlation length and the Curie temperature for both ferromagnetic electrode surfaces faced on the insulator. © *2000 American Institute of Physics.* [S0021-8979(00)54408-9]

I. INTRODUCTION

Recently, there has been a great deal of interest in the magnetoresistive properties of ferromagnetic tunnel junctions.[1,2] These junctions are potentially applicable in magnetoresistive reading heads, magnetic field sensors, and nonvolatile magnetoresistive random access memories (MRAMs).[3,4] In spite of the large tunneling magnetoresistance (TMR) effect, magnons at the interface between a ferromagnetic electrode and an insulator contribute to the decrease of the TMR ratio at higher voltages.[5] It is urgently necessary to reduce this large voltage dependence. We have reported on the measurements of conductive properties for Al/Al-oxide/Co/Al junctions using inelastic-electron-tunneling spectroscopy (JETS).[6,7] The phonons of the Al-oxide and the magnon excitation of Co were successfully observed in the spectra of the junctions with $d_{Co} \geqslant 10$ Å. In order to clarify the relationship between spin dependent tunneling properties and interface structure, IETS of ferromagnetic tunnel junctions have been carried out.[8] In this article, we report the spectra for the parallel (P) and antiparallel (AP) magnetization configurations of the both ferromagnetic electrodes. It separates only the magnon excitations from all excitations for the junction.

II. EXPERIMENTAL PROCEDURE

The spin-valve-type tunnel junctions were prepared by rf magnetron sputtering with inductively coupled plasma (ICP) onto a thermally oxidized Si substrates at an argon pressure of 0.07 Pa. The base pressure was below 5×10^{-6} Pa and the sputtering was carried out in an atmosphere of 0.08 Pa Ar. The layer structure was Ta(50 Å)/$Fe_{20}Ni_{80}$(60 Å)/IrMn(300 Å)/Co(60 Å)/Al(13 Å)-oxide/Co(40 Å)/$Fe_{20}Ni_{80}$(200 Å). The 100-μm-wide bottom electrode of Ta/$Fe_{20}Ni_{80}$/IrMn/Co was deposited using a metal contact mask and covered by Al. An insulator was formed by ICP oxidation of the Al layer at 0.73 Pa O_2 and 100 W for 600 s. The top Co/$Fe_{20}Ni_{80}$ electrode was deposited on the insulator to form a cross-pattern junction with an area of $100 \times 100\ \mu m^2$. The $dI/dV-V$ curves and IET spectra, i.e., the derivative of conductance, were measured by a modulation method using a homemade electrical circuit.[6] In addition to a dc voltage sweep, an ac modulation voltage of 10 mV with a frequency of 5.05 kHz was applied to the junction. The first- and second-harmonic signals were detected using a lock-in amplifier. Positive bias voltage was defined as the current direction from the bottom to top electrode. These measurements were performed in a magnetic field up to 100 Oe at 4.2 K.

III. RESULTS AND DISCUSSION

Figure 1 shows the bias dependence of the TMR ratio for the tunnel junction calculated from the $dI/dV-V$ curves of both magnetization configurations. When the bottom electrode is positively biased (PB) there is a small peak at about 15 mV (solid line), and when it is negatively biased (NB) this feature is not present (broken line). Since the rate of decrease of the TMR is initially smaller for PB, the two curves cross each other at a voltage of 70 mV. The dotted line indicates the calculated result taking into consideration the elastic tunneling process,[9] which is nearly parabolic and differs significantly from the present experimental result. Therefore, the large decrease in the TMR ratio is likely to be caused by the inelastic tunneling process. The average barrier height and width estimated from $I-V$ curves were 2.0 eV and 12.0 Å, respectively. Inset shows the MR curve measured at 4.2 K. Since the exchange bias from the IrMn antiferromagnetic layer is larger than 100 Oe, this curve is the

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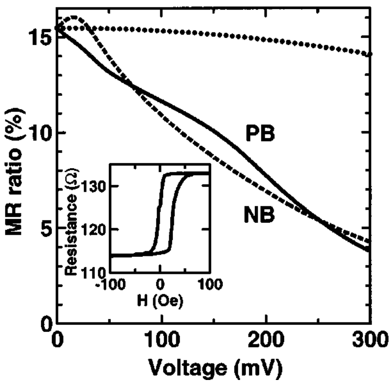

FIG. 1. The bias dependence of the TMR ratio for the Ta(50 Å)/$Fe_{20}Ni_{80}$ (60 Å)/IrMn (300 Å)/Co (60 Å)/Al(13 Å)-oxide/Co(40 Å)/$Fe_{20}Ni_{80}$ (200 Å) spin-valve-type tunnel junction. The solid and broken lines indicate the positive and negative bias voltage, respectively, and the dotted line indicates the calculated result taking into consideration the elastic tunneling process. Inset shows the MR curve measured at 4.2 K.

minor loop. Magnetic fields of −40 Oe for the P configuration and 30 Oe for the AP configuration were selected hereafter.

Figure 2(a) and 2(b) show the IET spectra for the P and AP magnetization configurations, respectively. The results for both the PB (solid line) and NB (broken line) voltages are shown. A strong positive peak at 12 mV is observed for all curves. The typical phonon spectra of the Al (33 mV) and the Al–O longitudinal optical (LO) mode (120 mV), which were observed for the Al/Al-oxide/Al junction,[6,7] are not detected. The strong peak is not conclusively the cutoff effect for measurement near the zero-bias arising from limitation of the modulation voltage, because the peak is located higher than the modulation voltage of this measurement. The spectra for AP configuration are larger than those for P configuration. Note also that these spectra are asymmetric with respect to the PB and NB directions. The different Fermi energy between both electrodes cause the asymmetry of the conductance curve, however, the elastic tunneling process cannot affect the IET spectrum.

IET spectra include all inelastic excitations, e.g., phonons, magnons, and the background conductance. The phonon inelastic excitation and the background conductance are spin-independent processes and do not affect the IET spectra by applying an external magnetic field. Consequently, the difference between the spectra for the P and AP magnetization configurations is expected to be only the spin-dependent processes, that is, a magnon-assisted inelastic electron tunneling process. Figure 2(c) shows the subtraction spectrum which is obtained by subtracting the spectrum of the P magnetization configuration from that of the AP configuration. They show a strong peak at V_P of 12 and 20 mV for the PB and NB directions, respectively. And also, note that the subtraction spectrum for the NB direction at a voltage between 16 and 170 mV becomes larger than that for the PB direction, while this feature is not present for the original IET spectra. The tendency of the TMR ratio to decrease agrees with the shape of the subtraction spectrum, namely, the larger the power of the subtraction spectrum, the faster the TMR ratio decreases with the bias voltage.

This subtraction spectrum must be an exact inelastic excitation spectrum induced only by the magnetic origin and might relate to the magnon density of states of the ferromagnetic electrodes. Magnon-assisted inelastic tunneling currents for the P and AP magnetization configurations can be expressed as[9]

$$I_P=\frac{2\pi e}{\hbar}\sum_{\alpha} X^{\alpha} g_{\downarrow}^{L} g_{\uparrow}^{R} \int d\omega \rho_{\alpha}^{\mathrm{mag}}(\omega)(eV-\omega)\,\theta(eV-\omega), \tag{1}$$

$$I_{AP}=\frac{2\pi e}{\hbar}\Big[X^{R} g_{\uparrow}^{L} g_{\uparrow}^{R} \int d\omega \rho_{x}^{\mathrm{mag}}(\omega)(eV-\omega)\,\theta(eV-\omega) + X^{L} g_{\downarrow}^{L} g_{\downarrow}^{R} \int d\omega \rho_{L}^{\mathrm{mag}}(\omega)(eV-\omega)\,\theta(eV-\omega)\Big], \tag{2}$$

where X is the incoherent tunnel exchange vertex, $\rho_{\alpha}^{\mathrm{mag}}(\omega)$ is the magnon density of states that has a general form $\rho_{\alpha}^{\mathrm{mag}}(\omega)=(\nu+1)(\hbar\omega)^{\nu}/E_m^{\nu+1}$, the exponent ν depends on a type of spectrum, E_m is the maximum magnon energy, $g^{L(R)}$ marks the corresponding electron density of states on left (right) electrode, $\theta(x)$ is the step function, $\alpha=L,R$. As one can see from Eqs. (1) and (2), the magnon-assisted inelastic tunneling current is asymmetric with respect to the PB and NB directions. Especially for the AP magnetization configuration, the first term in Eq. (2) can be dominant because $g_{\uparrow}^{L} g_{\uparrow}^{R}$ is much larger than $g_{\downarrow}^{L} g_{\downarrow}^{R}$. Therefore, the IET spectrum for the AP configuration is more sensitive to ρ_{R}^{mag}, that is, the difference between the spectra for the PB and NB directions is likely to reflect the difference between the magnon density of states of both electrodes.

The magnon density of states should increase monotonously or be constant for a bulk ($\nu=0.5$) or a surface ($\nu=0$) magnon, respectively, with increasing bias voltage. However, the spectra of the experiment have an obvious peak at the low bias voltage V_P. The decrease of the magnons below V_P might be related to the magnon cutoff energy,

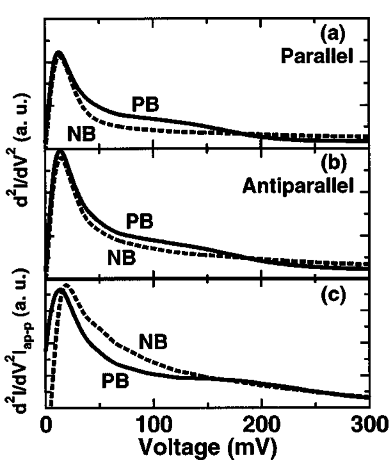

FIG. 2. The IET spectra for (a) the P and (b) AP magnetization configurations, respectively, and (c) these subtraction IET spectrum for the Ta (50 Å)/$Fe_{20}Ni_{80}$ (60 Å)/IrMn (300 Å)/Co (60 Å)/Al (13 Å) - oxide/Co (40 Å)/$Fe_{20}Ni_{80}$(200 Å) spin-valve-type tunnel junction. The results for the both PB (solid line) and NB (broken line) voltages are shown.

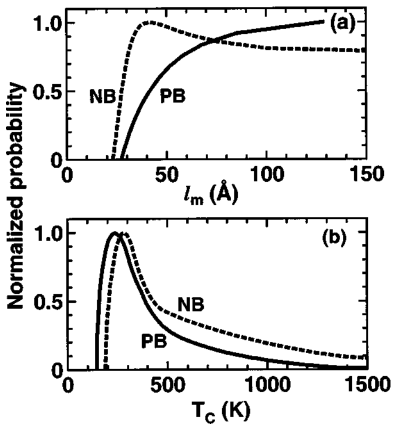

FIG. 3. The probability of (a) the correlation length of the surface magnon l_m and (b) the Curie temperature T_C, respectively, for both the positively and negatively biased directions.

namely, the lowest energy (voltage) at which a magnon can be excited due to the limitation of the size of the ferromagnet. If the structure of the interface between the ferromagnet and the insulator is not perfect, possibly due to the roughness of the film, the correlation length l_m for a magnon excitation may be reduced to a finite value. On the other hand, the decrease of the magnons over V_P might be related to the maximum energy of magnon excitation E_m, which can be expressed by the mean-field approximation as $E_m \cong 3k_B T_C/(S+1)$.[10] T_C and S are the Curie temperature and the spin of a ferromagnet, respectively. If l_m and T_C fluctuate due to the inhomogeneity of the interface, the shape of the subtraction spectrum will reflect the distributions of l_m and T_C. By considering the surface magnon, we can calculate the probability of l_m and T_C. We fixed the boundary at V_P and the subtraction spectrum below and above V_P were assumed to depend only on the distribution of l_m and T_C, respectively. Figures 3(a) and 3(b) show the probability of l_m and T_C, respectively, for both the PB and NB directions. Here, we take $S=3/2$. Smaller l_m is dominant for the NB direction; the peak is located at about 40 Å, while it is slightly lower for the PB direction. The minimum value is about 25 Å, which does not differ greatly from the grain size determined by conducting atomic force microscopy (AFM)[11] or the cross-section of TEM measurement. The distribution of T_C for the NB direction shifts slightly to higher temperature than that for PB direction. As mentioned above, the asymmetry with respect to the sign of the bias voltage reflects the difference in the density of states of magnons of both interfaces. This might come from the difference in the structure of the both interfaces. If the inelastic tunneling process for AP magnetization configuration emphasizes the magnon excitation at negatively biased electrode, the structure of the interface at bottom ferromagnetic electrode should be characterized as the distribution for the PB direction. It is still not clear where the difference comes from, however, and is considered to be related the damage during the oxidation process, the diffusion of O_2 from the insulator, and also the different crystal growth and the roughness of the ferromagnetic electrodes. Obviously, observation of the subtraction spectrum is important in order to understand the bias-voltage dependence of the TMR and its relationship to the interface structure. Systematic experimental data for the inelastic excitation spectrum is required in order to discuss these matters.

IV. SUMMARY

The IET spectra for the Ta/$Fe_{20}Ni_{80}$/IrMn/Co/Al-oxide/Co/$Fe_{20}Ni_{80}$ spin-valve-type tunnel junction were measured at the P and AP magnetization configurations of both ferromagnetic electrodes. By calculating the subtraction of the spectrum of the P configuration from that of the AP configuration, we obtained the inelastic excitation spectrum only of magnetic origin. The tendency of the TMR ratio to decrease with the bias voltage agreed with the shape of the subtraction spectrum, which could be explained by considering the distributions of the correlation length for the surface magnon excitation and the Curie temperature at the ferromagnetic electrode surface faced on the insulator. The asymmetry of the spectrum to the sign of the bias voltage is considered to arise from the different structure of the both interfaces.

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