Voltage induced magnetic anisotropy change in ultrathin Fe80Co20/MgO junctions with Brillouin light scattering

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Voltage induced magnetic anisotropy change in ultrathin $Fe_{80}Co_{20}$/MgO junctions with Brillouin light scattering

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We investigate voltage induced perpendicular magnetic anisotropy (PMA) changes in MgO/Cr/Au/$Fe_{80}Co_{20}$/MgO/polyimide/ indium tin oxide (ITO). In order to observe the PMA change, spin wave frequency was measured by Brillouin light scattering with finite bias voltages applied between Au and ITO electrodes. The obtained PMA constants from spin wave frequency of $Fe_{80}Co_{20}$ layer show clear bias voltage dependences, which agree well with the previous polar-Kerr effect measurement results and theoretical study. This study suggests spintronics devices operated by an electric field for next generation devices complying with low-power consumption. [doi:10.1063/1.3385732]

The needs for a faster speed and a higher density of storage devices have led spintronics technology such as spin torque transfer magnetic random access memory (STT-MRAM) operated by switching direction of a magnetization of free layer in magnetic tunneling junction.[1] The switching mechanism in STT-MRAM is altering angular momentum by the spin polarized current, not a conventional Zeeman energy minimization with an external magnetic field. Since the required current density for the switching is not yet adoptable for low power consumption, an alternative approach has been suggested. The promising approach is manipulating magnetic properties with an electric field, or bias voltage. The devices based an electric field have superior benefits of low power consumption. Recently, many epochal experimental[2–11] and theoretical[12–16] studies have been reported with various heterojunction structures for bias voltage controlled devices. The electric field induced manipulations of the magnetization have been reported within multilayer stacks including piezoelectric materials,[2] ferromagnetic semiconductors,[3–5] multiferroic materials,[6] or magnetoelectric interface.[7–11] The several successful demonstrations are based on the variation in magnetic anisotropy energy with the electric field. Weisheit *et al.*[8] demonstrated the 4.5% coercivity change in FePt (or FePd) film in the structure include liquid electrolyte by applying an electric field. Recently, it has been reported that the perpendicular magnetic anisotropy (PMA) of ultrathin magnetic layers (Fe and $Fe_{80}Co_{20}$) can be altered by applying bias voltages.[10,11] Since the structure is all-solid-state and very similar to well optimized MgO based MTJ, these studies have important distinction compare to the formers. In the previous studies,[10,11] however, the observed PMA changes which were obtained from polar-Kerr hysteresis measurement, and it has disadvantages such as low accuracy and restrictions of low field regions.

In this study, we would like to evaluate the PMA energy from a qualitative analysis by employing Brillouin light scattering (BLS) measurement. The BLS measurement is powerful tool for investigating PMA (Refs. 17–21) as well as various magnetic properties such as in-plane magnetic anisotropy, effective magnetization, and dispersion relation. So, we could evaluate PMA constants from investigating the spin wave frequencies of several thicknesses of $Fe_{80}Co_{20}$ layer for various bias voltages.

As the schematic sample structure shown in Fig. 1, the multilayer stack consist of MgO/Cr(10 nm)/Au(50 nm)/$Fe_{80}Co_{20}$(d nm)/MgO(5 nm)/polyimide(1500 nm)/ indium tin oxide (ITO)(100 nm). The $Fe_{80}Co_{20}$ layer was deposited by co-evaporation method as wedge type in the range of $0 \sim 0.75$ nm thickness. The bias voltage is applied between bottom Au and top ITO electrodes. Since ITO electrodes are 500 μm radius circles and they are transparent for visible light, optical measurements can be performed for specific thickness of $Fe_{80}Co_{20}$ after focus on the positions to investigate. Since polymide layer is also transparent, the spin wave frequency can be measured with scattered light from $Fe_{80}Co_{20}$ layer. The polymide layer was coated by spin-coater to ensure pinhole-free barrier. Except polymide and ITO layer, the multilayer was grown by a molecular beam epitaxy method in ultra high vacuum (UHV) chamber.[12] Here, the positive sign of bias voltage V_b is defined as a state

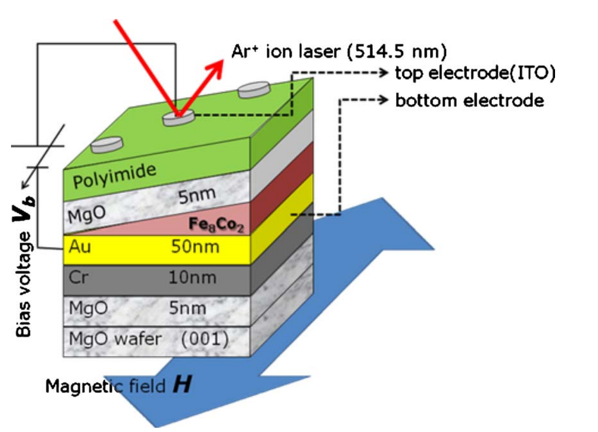

FIG. 1. (Color online) Schematic for a structure of the sample and BLS measurement. The structure consist of MgO/Cr/Au/$Fe_{80}Co_{20}$/MgO/polyimide/ ITO, and wedge shaped $Fe_{80}Co_{20}$ layer was investigated several thickness for 0.55, 0.6, and 0.65 nm.

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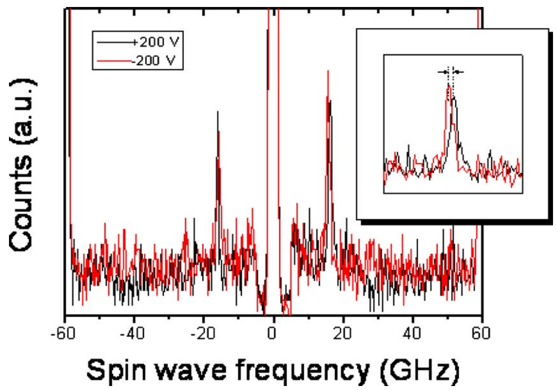

FIG. 2. (Color online) Spin wave spectrum obtained from 0.55 nm $Fe_{80}Co_{20}$ layer of the sample for applying +200 V (black line) and −200 V (red line). In the positive frequency region, the peak indicating frequency of a surface magnon shifts (arrows of inset) for each different $\boldsymbol{V_b}$.

that an electric potential of ITO (top electrode) is higher than the potential of Au (bottom electrode).

We examined the magnetic properties of the sample for several thickness of $Fe_{80}Co_{20}$ by using BLS measurement. The backscattered light was analyzed by a Sandercock type (3+3)-pass tandem Fabry–Pérot interferometer.[22,23] A frequency shift from the frequency of Ar^+ ion laser ($\boldsymbol{\lambda}$=514.5 nm) that corresponds to a thermally excited magnon frequency of the sample has been recorded. In this study, we measured the spin wave frequency as a function of the external magnetic field to investigate PMA. The magnetic field was applied parallel to the sample surface and perpendicular to the incident plane of the light in the range of 0–5 kOe. The incident angle of the light was fixed as 45° from a sample plane. All measurements were performed *ex situ* at room temperature. In order to investigate spin wave frequency for various thickness of the $Fe_{80}Co_{20}$ layer, incident beam exposed to specific ITO electrodes over different $Fe_{80}Co_{20}$ thicknesses. Also, the effect of V_b to PMA was investigated with applying voltage in the range from −200–200 V by digital source meter (Keithley, model 2400).

Figure 2 shows spin wave spectra obtained from 0.55-nm thick $Fe_{80}Co_{20}$ layer for applying +200 V (black line) and −200 V (red line) with in-plane external magnetic field of 5 kOe. In the positive frequency region near 18 GHz, the peak indicating frequency of a surface magnon shifts (arrows in the inset) for each V_b. This shift shows that spin wave have an obvious dependence of V_b. When V_b is applied to the junction, the changes in spin wave frequency depend on the sign of V_b. In Fig. 3, each graph shows measurement results with two bias voltages (+200 and −200 V) for several different $Fe_{80}Co_{20}$ thicknesses (d=0.55, 0.6, and 0.65 nm). The square dots indicate BLS measurement data and solid lines are fitted curves with the equation modified from uniform spin wave mode for a PMA sample.[17] The equation is given as

$$(\omega/\gamma)^2 = H(H + [4\pi D_\perp M_S]_{\mathrm{eff}}), \tag{1}$$

$$(4\pi D_\perp M_S)_{\mathrm{eff}} = 4\pi D_\perp M_S - 2K_S/M_S d. \tag{2}$$

In this expression, K_S and $D_\perp$ are the first order uniaxial surface anisotropy constant and demagnetizing factor which was evaluated as 1–0.2338/number of layers is near 0.9.[24] Here, K_S includes surface magnetic anisotropies on both interfaces of $MgO/Fe_{80}Co_{20}$ ($=K_S^{\mathrm{MgO/FeCo}}$) and $Fe_{80}Co_{20}/Au$ ($=K_S^{\mathrm{FeCo/Au}}$). In addition, it also includes the bias voltage induced surface magnetic anisotropies changes, $K_S^{V_b}$. Though, these surface anisotropies cannot be separated by our measurement method, it is allow to identify an effect of V_b. When the magnetic field is applied parallel to plane of magnetic thin film which has PMA, the spin wave frequency decreases with increasing H until the magnetization is tilted into the plane of the film at critical field H_{cri}. For further increasing fields, the frequency increases with magnetic field.[25] Figure 3 shows behavior of spin wave frequency in high field region over H_{cri} for several d and V_b. Our BLS setup cannot identify the magnon peaks under 3 GHz regions, since it is screened by strong and wide Rayleigh peak. Even though the under 3 GHz data was missing due to measurement limitation, the influence on the V_b and d are clearly shown by the shift in the line. When V_b=0, the evaluated PMA constants K_S are 0.94, 0.864, and 0.818 mJ/m^2 for 0.55, 0.6, and 0.65 nm $Fe_{80}Co_{20}$ layers, respectively. Shiota *et al.*[11] estimated surface anisotropy as 0.65 mJ/m^2 for d=0.58 nm, and considering different d and evaluating method, this value is reasonable compared to the present result (0.94 mJ/m^2 for d=0.55 nm). Also, it must be noted

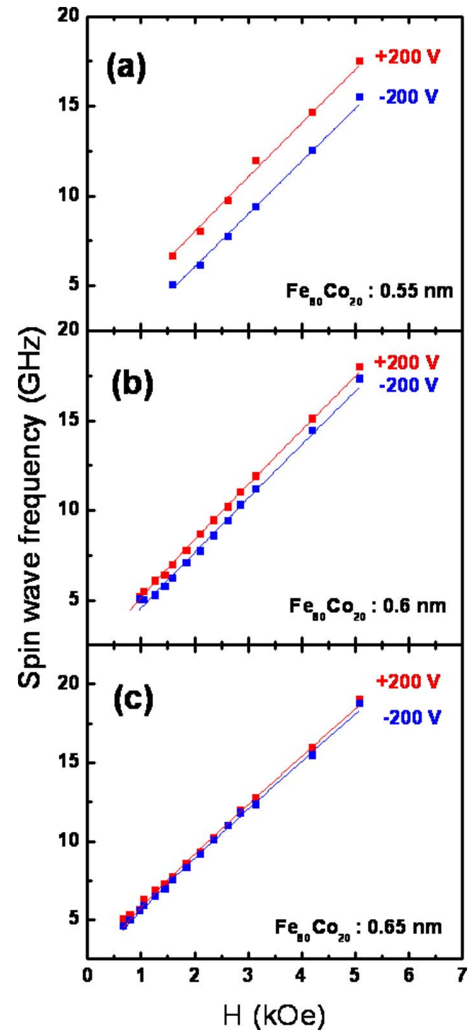

FIG. 3. (Color online) Dependence of the spin wave frequency on the applied magnetic field for various bias voltages. The results from BLS measurement (closed square) were fitted to the Eq. (1) as shown by solid lines for three bias voltage, −200 (red) and +200 V (blue). The PMA change in 0.55 nm thick $Fe_{80}Co_{20}$ is larger than others (0.6 and 0.65 nm).

that the obtained K_Ss give reasonable agreement with the values observed in metallic sandwiched layers.[17,19] The evaluated critical fields corresponding each thickness of $Fe_{80}Co_{20}$ layers are −0.23, −3.2, and −5.3 kOe, which implies that though the shape anisotropy is stronger than the perpendicular surface anisotropy in this system, PMA increases with decreasing thickness of magnetic layer. According to previous study,[11] at near $d=0.58$ nm the system has a transition that direction of easy axis changes from in-plane to out of plane. In other hands, the PMA changes, ΔK_S [$=K_S(-200\ \text{V})-K_S(+200\ \text{V})$] are 0.077, 0.032, and 0.013 mJ/m^2 for 0.55, 0.6, and 0.65 nm thick $Fe_{80}Co_{20}$ layers, respectively. Since the electric field corresponding to $\Delta V_b=400$ V equal to 92.4 mV/nm at the interface of $Fe_{80}Co_{20}$/MgO,[10] we can deduce $\Delta K_S=0.833$, 0.346, and 0.140 mJ/m^2 PMA changes for each thickness for the electric field of 1 V/nm. These results show good agreement in the sign of the anisotropy change, even though are somewhat larger than the first principle calculation result,[13] where they reported 0.02 mJ/m^2 PMA change in Fe/vacuum interface for 1 V/nm electric field. We also find that ΔK_S have unexpected thickness dependence, which cannot be explained with surface anisotropy model, it is requires further study. We found $\Delta K_S/\Delta V_b<0$ in all thickness range, it implies that PMA increases with negative V_b. These results agree with the previous polar-Kerr measurement (Figs. 2 and 3 in Ref. 11). The effective electric field at the interface between MgO and $Fe_{80}Co_{20}$ layers might be different from the nominal value calculated from V_b, the effect of charge trap at polymide must be considered for proper interpretation as discussed in the supplementary information of Ref. 10. Even though this phenomenon cannot be well understood yet, spin wave frequency variation in the electric field is obvious evidence of voltage induced PMA changes.

The possible physical origins of electric field induced PMA change have been proposed. Kyuno[26] found that the PMA is sensitive on the band filling. And the field induced extra charge at the interface may cause of the PMA change. Other possible mechanisms have been claimed: PMA in Fe(001) layer can be modified by components of p orbital near Fermi energy coupled to the d states,[13] while one deduces that PMA change is from large density of states of d_{xy} and $d_{x^2-y^2}$ in the Fermi energy level for case of the system which has a large spin-orbit coupling.[10] More recently, Nakamura[14] suggested that the band structure itself can be modified by the electric field. In current stage, the experimental data cannot give any relevant information with theoretical studies but the experimentally observed ΔK_S is in the same order of magnitude of theoretical results.

In conclusions, we investigated PMA variation in MgO/Au/$Fe_{80}Co_{20}$/MgO/polymide/ITO junction with finite bias voltages. We confirmed that the finite bias voltage leads the PMA changes by the BLS measurement. With the careful analysis of the BLS data, the qualitative ΔK_S (0.833, 0.346, and 0.140 mJ/m^2 for 1 V/nm) values are obtained. We believe that the voltage controlled PMA will pave the new way for the low power consumption spintronics devices.

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