

Microscopic mechanisms of the electric-field effect on proximity-induced magnetism in Pt revealed by X-ray absorption spectroscopy

Carrier doping in condensed matter by an electric field is a principal technology for operating electronic devices. Electric fields are also used to control the magnetic properties of not only ferromagnetic semiconductors [1] but also thin ferromagnetic metals [2], such as Fe and Co. In particular, electric-field-assisted magnetization switching in ferromagnetic metals [3] is promising for the energy-efficient operation of magnetic memory devices. However, despite the potential applications, the mechanisms of the electric-field effect on ferromagnetism are still controversial because of the lack of experimental study.

In this research [4], we unraveled the microscopic mechanisms of the electric-field effect on proximity-induced magnetism in Pt by X-ray magnetic circular dichroism (XMCD) and X-ray absorption spectroscopy (XAS) performed at SPRING-8 BL39XU. Pt atoms in the proximity of a ferromagnetic layer can be ferromagnetic. "Ferromagnetic Pt" has interesting characters: a small exchange splitting and strong spin-orbit interaction. Because the coexistence of the two factors can enhance the electric-field effect on the magnetic anisotropy [5], ferromagnetic Pt has been attracting attention. XMCD and XAS spectroscopy are powerful tools for scrutinizing the electric-field effect. An XMCD spectrum contains information about the magnetic polarization of a specific element and, importantly, enables us to evaluate the spin and orbital magnetic moments by using the sum rules. By analyzing the XAS spectrum obtained under the application of an electric field, one can examine how the applied electric field affects the unoccupied electronic states.

In our experiments, we employed an ionic liquid

to apply a large electric field to a Pt channel of an electric-double-layer transistor formed on a synthetic quartz glass substrate (see Fig. 1). By applying a gate voltage (V_G) between the channel and lateral gate electrodes, the ions move onto the channel surface to form an electric double layer, equivalent to a nanogap capacitor. Here, applying a positive V_G causes the accumulation of electrons at the Pt/MgO interface. The experimental configuration is schematically shown in Fig. 1. A magnetic field was applied perpendicular to the device surface and a circularly polarized X-ray propagated parallel to the magnetic field direction. We measured the fluorescence yields of the Pt L_{α} and L_{β} lines as a function of X-ray energy at the Pt L_3 and L_2 edges, respectively. The XAS and XMCD intensities are defined as $I_{XAS} = [I(\sigma^+) + I(\sigma^-)]/2$ and $I_{XMCD} = I(\sigma^+) - I(\sigma^-)$, where $I(\sigma^+)$ and $I(\sigma^-)$ indicate the intensities of X-ray fluorescence when the incident photon momentum and magnetization vectors are antiparallel and parallel, respectively. Throughout the X-ray measurements, the device was located in an evacuated chamber of a He-flow cryostat and the measurement temperature was fixed at 100 K.

Figure 2 shows I_{XMCD} and I_{XAS} at $V_G = +6$ and -4 V together with their differences, ΔI_{XMCD} and ΔI_{XAS} , between the two voltages. The significant changes in I_{XMCD} and I_{XAS} indicate that the applied electric field modulates the magnetic moments and electronic states of Pt. By applying the sum rules to values of the I_{XMCD} measured at different V_G 's, the perpendicular components of the effective spin and orbital moments are estimated to be 0.222 ± 0.001 (0.232 ± 0.002) μ_B and 0.043 ± 0.001 (0.047 ± 0.001) μ_B at $V_G = +6$ (-4) V, respectively. The voltage-induced changes in I_{XAS} indicate that the electronic states above the Fermi

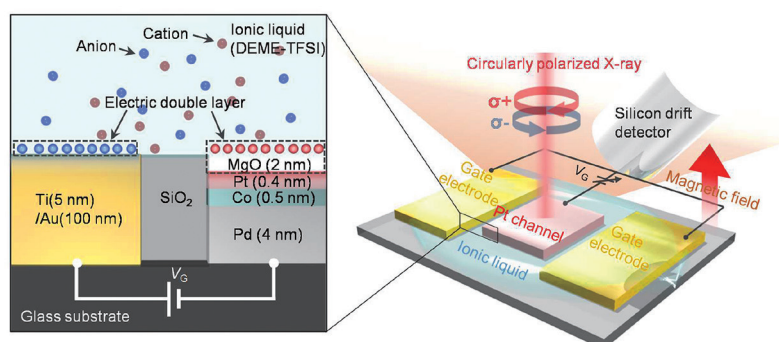


Fig. 1. Schematic illustration of the experimental configuration.

energy (E_F), i.e., the number of 5d holes, change upon the application of an electric field. The total number of 5d holes of Pt increases by ~ 0.009 when V_G is switched from +6 V to -4 V. Note that the spectral profile of the XAS difference (ΔI_{XAS}) is not monotonic with the X-ray energy; ΔI_{XAS} changes sign around 11.571 and 13.290 eV for the L_3 and L_2 absorption edges, respectively. The reductions of ΔI_{XAS} near the absorption edges are mostly due to the electric-field-induced shift of E_F , simply corresponding to the electrostatic charge accumulation. Then, ΔI_{XAS} becomes positive at the high-energy sides of the absorption edges, which cannot be explained by the electrostatic charge accumulation. The electric field can also alter the hybridizations between the sp and d orbital of Pt. This mechanism is considered to increase (decrease) the number of 5d holes of the Pt atoms under a positive (negative) electric field. The changes

in I_{XMCD} and I_{XAS} were well reproduced by a density functional theory calculation. Scrutinizing the electronic structures under electric fields, we find that the two mechanisms (electric-field-induced shift of E_F and changes in the orbital hybridizations) indeed give rise to the nonmonotonic changes in I_{XAS} and are relevant to the modulated magnetic moments of the Pt atom.

The experimentally unveiled mechanisms of the electric-field effects in ferromagnetic Pt are expected to give us a fundamental model applicable to a wide range of ferromagnetic metals, represented by Fe and Co. Furthermore, the highly sensitive XMCD and XAS measurements under the application of electric fields enabled us to correlate the changes in the magnetism with the microscopic picture. This research has demonstrated the significant benefit of XAS for investigating magnetic phenomena induced by external fields.

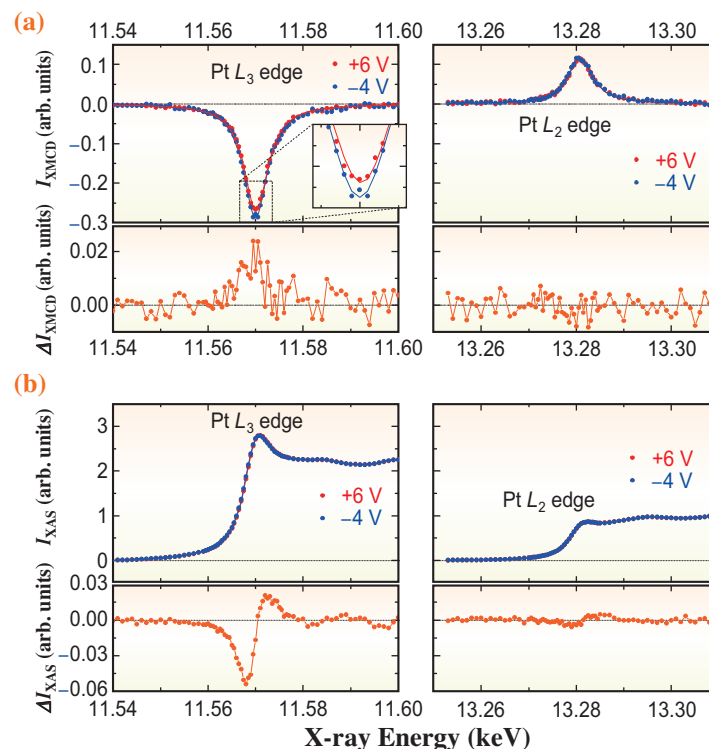


Fig. 2. (a) XMCD (I_{XMCD}) and (b) XAS (I_{XAS}) intensities at Pt L_3 and L_2 edges for $V_G = +6$ and -4 V and their difference $\Delta I_{XMCD(XAS)} [= I_{XMCD(XAS)} (+6 \text{ V}) - I_{XMCD(XAS)} (-4 \text{ V})]$.

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