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Anomalous Hall effect in one monolayer cobalt with electrical manipulation

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We investigate electrical manipulation of magnetism in Ta/Pd/Co/HfO_2 films probed by anomalous Hall Effect (AHE). The coercivity of the one monolayer cobalt and the transition temperature for the disappearance of usual AHE curves could be modified by a low voltage below ±2 V via the usage of ionic liquid. The unexpected emergence of inverted Hall loops above the transition temperature but far below the Curie temperature performed on the magnetometer could be explained by the competition between skew scattering and intrinsic/side-jump contributions of AHE. Our finding provides a different avenue for exploring the origin of AHE by electrical manipulation.

Electric-field gating offers an effective route to confine electrons in nano-scale regions [1–3]. Compared with the conventional electric current control of magnetism, such as spin transfer torque, which needs a current density of 10^6 A/cm^2, electric-field-induced magnetization is expected to dramatically reduce the power consumption in data storage devices [1,4]. Magnetization controlled by electrical means have been realized in various materials, such as diluted magnetic semiconductors [2,5,6], metals [7], and magnetoelectric multiferroics [8,9]. Field induced modulation of magnetic properties include coercive field, Curie temperature, domain wall motion and electronic phase transition have been achieved through modulation of carrier density, shuttle movement of oxygen ions, or internal carrier localization [2,7,10–15].

The application of voltages via a gate electrode for magnetization modulation is intrinsically identical to the field effect transistor.[1] Since the first observation of electrical control of ferromagnetism in perpendicular magnetized (Ga,Mn)As and the subsequent works always referring to ultrathin metallic systems (such as Co/Pd), the detection of the electric field effect is commonly carried out via anomalous Hall effect (AHE) measurements [2,7]. It is well known that the origin of AHE has been persistently an open question in materials physics due to interesting underlying physics and great potential applications, despite intensive theoretical and experimental studies in these years [16–26]. It is now extensively accepted that there are three mechanisms responsible for the AHE: the intrinsic one arising from the transverse velocity of the Bloch electrons [16,17], and the extrinsic mechanisms of skew scattering and side jump of conduction electrons [18,19]. Nevertheless the mechanisms for the AHE are still in a strong debate. For instance, a review by Sinitsyn [20] excludes the possibility of intrinsic origin, but recent experimental results supporting this mechanism [21,22]. The use of selective material systems suitable for AHE research, transition metals, complex oxide ferromagnets and ferromagnetic semiconductors, etc., as well as tuning their chemical ordering and temperature dependence are typical approaches to understanding the mechanisms of AHE [16,23–27].

However, the scaling relationship of AHE between different materials basically cannot be comparable. Changing the structure or chemical composition of a system is widely accepted, but generally only the dependence of AHE on external factor such as thickness and doping ratio can be obtained [23–27]. The additional impurity scattering and variation of spin-orbit coupling to Berry wave functions are often induced in these experiments [28,29], which undoubtedly complicate the exploration of origin of AHE. Now the research interest is whether an elegant approach could modify the anomalous Hall resistance, but no extra factors superimposes, providing a unique opportunity to understand AHE in a certain material. Here we use the electric field provided via ionic liquid to manipulate the magnetic properties of one monolayer

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cobalt film with perpendicular magnetic anisotropy (PMA), which are monitored by the variation of AHE.

The heterostructures Ta(5 nm)/Pd(5 nm)/Co(0.26 nm)/HfO_2 (2 nm) were deposited on Si/SiO_2 substrates using electron beam evaporation with a background pressure of 5×10^{-9} Torr [30]. Magnetization measurements of the films were carried out using a superconducting quantum interference device (SQUID) magnetometer. The films were then patterned into Hall bar structure with the channel width of 100 μm using photolithography and ion milling. A drop of ionic liquid was directly placed in the middle of Hall bar on top of HfO_2 as the electrolyte, connecting the gate electrode and Hall cross, as depicted in Fig. 1(a). The ionic liquid is *N*,*N*-diethyl-*N*-(2-methoxyethyl)-*N*-methylammonium bis-(trifluoromethylsulfonyl)- imide (DEME-TFSI). Electric field effect was built by external voltage source at room temperature and then cooled to 100 K when ionic liquid solidifies and the field was stable. Hall resistivity (ρ_{Hall}) and longitudinal resistivity (ρ_{xx}) were studied in physical property measurement system, with the external magnetic field (H) applied perpendicular to the sample plane and a constant current of 100 μA. Compared with conventional solid gate insulator, the electric double layer (EDL) transistor has been developed as a powerful device structure allowing an extremely high electric field effect on the ultrathin Co layer [Fig. 1(b)] [31].

We point out that 2 nm-thick HfO_2 (a high-permittivity material) is capped to prevent the direct chemical reaction between metallic Co and ionic liquid. Although the existence of HfO_2 in our experiment would weaken the electric field by adding an extra thickness of 2 nm to the original thickness of EDL, the electric field effect generated here is still much larger than that of simply using traditional ~100 nm-thick dielectric layers. On the other side, the interaction between Co atoms and O^{2-} ions, i.e., the formation of an orbital hybridization or Co–O bond at Co/HfO_2 interface, contributes to the PMA of the system [32,33].

Magnetization curves at different temperatures at $V_G = 0$ are presented in Fig. 2(a). The squared shape of hysteresis loops indicates the strong PMA of the stacks, with the coercive field of 12.5 kOe at 10 K and 70 Oe at 300 K. It is quite impressive to acquire clear AHE signals in the sole single-period Co monolayer at room temperature. The relatively large coercive field, which could be explained by the strong interaction at Co/Pd interface, is favorable, because it could provide a possibly recognizable manipulation when the gate voltage (V_G) is applied. Note that the magnetization at 400 K remains clear with the saturation field of ~500 Oe, as presented in the inset of Fig. 2(a), indicating the Curie temperature (T_C) is above 400 K. Fig. 2(b) shows the moment–temperature (M–T) curve measured at $H = 20$ Oe. The data is only available below 400 K because of the temperature limit of SQUID. According to the Bloch's law, the magnetization can be fitted by $M \propto (1 - T/T_C)^{\beta}$ near T_C, where β is a critical exponent dependent on composition and greater than zero. The T_C can be estimated to be 416 K, higher than room temperature but much smaller than that of bulk Co (1388 K), which is mainly attributed to the low dimension of the present Co layer.

To reflect the electric field effect, the temperature dependence of longitudinal resistivity ρ_{xx} for different V_G is shown in Fig. 2(c). The value of ρ_{xx} drops with positive voltage $V_G = +0.5$ V while increases when external voltage turns to -0.5 V. This behavior might be caused by the electron carriers accumulation (depletion) under positive (negative) gate voltage [34], or the electroresistance effect when the carrier mobility is modulated by ionic liquid [35]. A closer inspection of the curves shows a stronger modification on resistance at negative V_G than at positive V_G. This difference can be

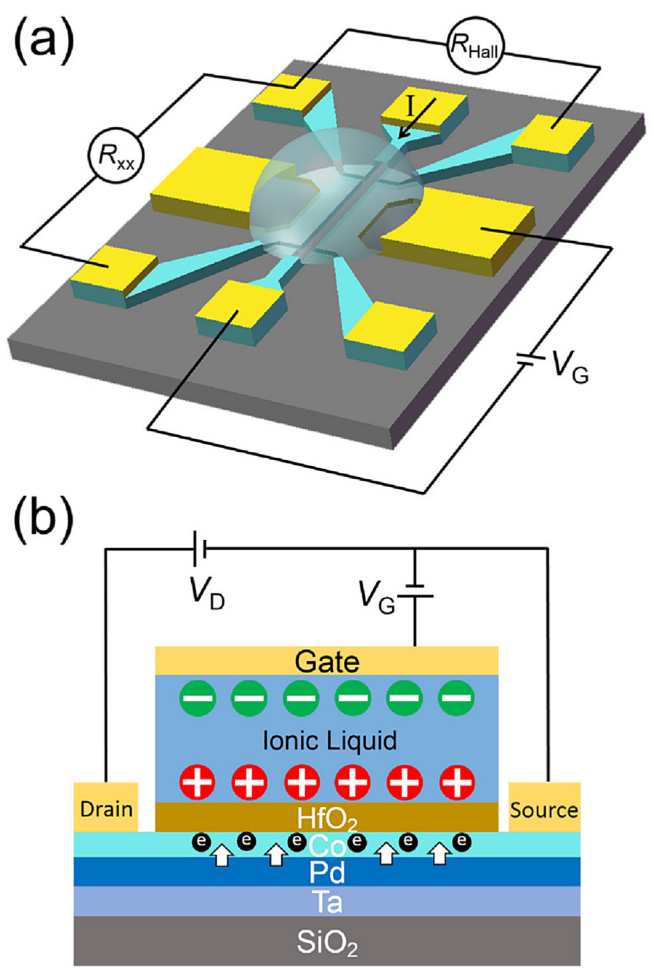

Fig. 1. (a) Schematics graph of Hall bar with ionic liquid covering the channel. (b) Illustration of accumulation of electrons carriers with positive gate voltage.

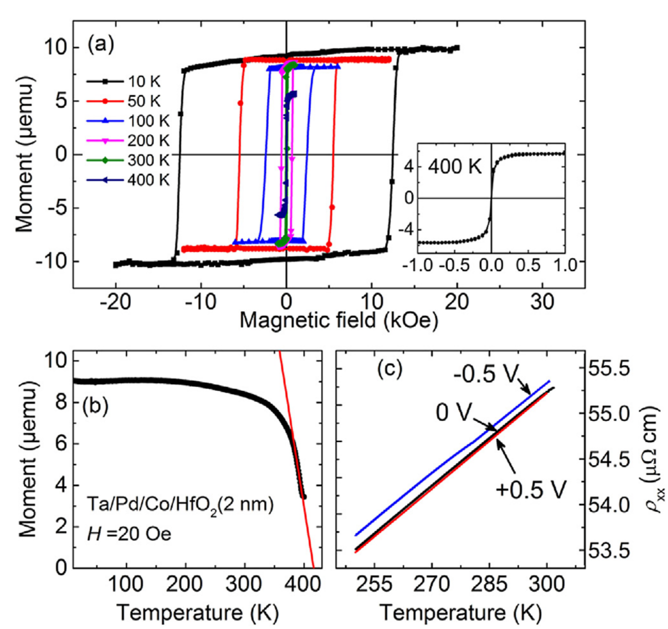

Fig. 2. (a) Magnetization loops at various temperatures with $V_G = 0$ V, the field is applied perpendicular to film plane, the inset shows the result at 400 K with a saturation field of ~500 Oe. (b) M–T curve from 10 K to 400 K, the straight line represent the extrapolation of magnetization up to ~416 K. (c) Temperature dependence of longitudinal resistivity for $V_G = 0$ V, +0.5 V and −0.5 V.