Non-Linear Anomalous Hall Effect in Few-Layer WTe_2

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Abstract:

The Hall effect occurs only in systems with broken time-reversal symmetry, such as materials under an external magnetic field in the ordinary Hall effect and magnetic materials in the anomalous Hall effect (AHE). Here we demonstrate a new Hall effect in a non-magnetic material, few-layer T_d-WTe_2 under zero magnetic field. In this effect, the Hall voltage depends quadratically on the longitudinal current. Our results open the possibility of exploring topological effects in solids by nonlinear electrical transport and applications of the phenomenon in spin-orbit torque devices.

Summary of Research:

The linear Hall effect is odd under time-reversal operation, it occurs only in systems with broken time-reversal symmetry (TRS). The second-order nonlinear effect, in which the Hall voltage depends on drive current quadratically, however, is even under time-reversal operation. It therefore does not require the application of an external magnetic field or the presence of magnetic order in the material. Furthermore, the effect is odd under space-inversion operation and is thus limited to systems with broken inversion symmetry. More specifically, the nonlinear anomalous Hall effect (AHE) has been predicted to exist in crystals with a polar axis and can be used to probe the topological properties of the solids such as the Berry curvature dipole [1]. The experimental studies of the nonlinear AHE remain elusive.

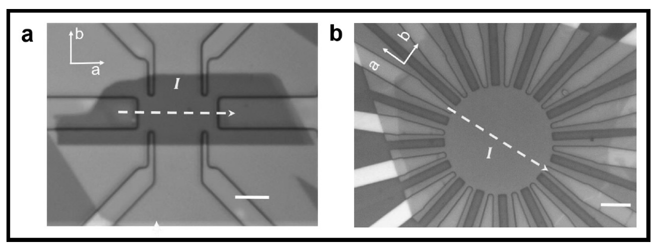


Figure 1: Optical image of a typical Hall bar (top) and circular disk (bottom) device used in this study. The scale bars are 5 m. WTe2 samples are in grey, Pt electrodes in orange, and the Si substrate in dark red-orange for the disk device, respectively. Dashed yellow lines indicate the current (I) direction. a and b are the crystal axes.

Here we investigate the nonlinear electrical properties of metallic few-layer T_d-WTe_2. Atomically thin T_d-WTe_2 has one polar axis along the crystal b axis, and thus allows the nonlinear AHE. Figure 1 shows the images of samples employed in the experiment. Figure 1a is a sample in the Hall bar geometry and the Figure 1b shows a sample in the circular disk shape. To fabricate these devices, few-layer WTe_2 and hexagonal boron nitride (hBN) were mechanically exfoliated from bulk crystals (HQ Graphene) onto silicon substrates. The hBN and WTe_2 flakes were picked up by a stamp consisting of a thin film of polycarbonate (PC) on polydimethylsiloxane (PDMS). The stack was then released onto a Si substrate with pre-patterned Pt electrodes. For disk devices, the completed stack was further patterned into a circular shape. To this end, a poly(methyl methacrylate (PMMA) mask with desired shape was first defined by standard e-beam lithography on top of the completed stack, it was then etched by reactive ion etching with SF_6 gas. Finally the residual PMMA was removed in an acetone bath.

To measure the nonlinear anomalous Hall effect in few-layer WTe_2 in the Hall bar devices, we apply an AC current along the crystal a-axis at a fixed frequency (137 Hz) and measure the longitudinal and transverse voltage drops at both the first and second-harmonic frequencies. The circular disk devices were measured in the same fashion. Current was injected from one of the 16 electrodes, voltages parallel and perpendicular to the current injection were recorded. The angular dependence of the nonlinear anomalous Hall effect was carried out by rotating both current injection and voltage measurement simultaneously.

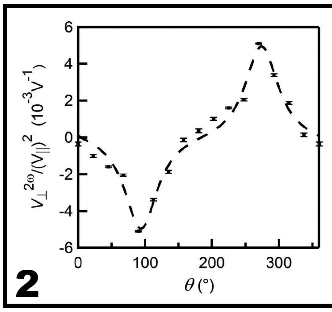
A second-harmonic transverse $V_{\perp}^{2\omega}$ voltage was observed in both the Hall bar and circular disk devices. Its magnitude scales quadratically with the current. In the disk devices, the normalized nonlinear hall response $V_{\perp}^{2\omega}/(V_{||})^2$ (where $V_{||}$ is the linear longitudinal voltage) shows a one-fold angular dependence (Figure 2). It maximizes when the current is perpendicular to the mirror line (i.e. along the a-axis), and minimizes when the current is parallel to the mirror line (i.e. along the b-axis). The observed effect is fully consistent with the crystal symmetry of few-layer T_d-WTe_2.

The microscopic mechanism of the observed effect was further examined by studying its scaling against scattering (conductivity σ).

The normalized nonlinear Hall response

$$\frac{E_{\perp}^{2\omega}}{(E_{\parallel})^2}$$

(where $E_{\perp}^{2\omega}$ and $E_{||}$ are the fields calculated from the corresponding voltages and the device dimensions) was observed to scale linearly with σ^2 for a large range of temperature (Figure 3). Such a scaling law suggests that the observed nonlinear Hall effect can be understood as an anomalous Hall effect with electrically generated magnetization. Our result also indicates that both intrinsic Berry curvature dipole and extrinsic spin-dependent scatterings contribute to the observed nonlinear AHE.



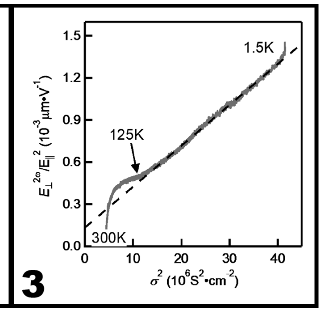


Figure 2, left: The nonlinear Hall effect as a function of current angle. Symbols are experimental data and the dashed line is a fit to the nonlinear response model including all second-order nonlinear susceptibilities allowed by the crystal symmetry. Figure 3, right: The normalized nonlinear Hall effect as a function of square of the longitudinal conductivity. The dashed line is a linear fit.

References:

[1] Sodemann, I., and Fu, L. Quantum Nonlinear Hall Effect Induced by Berry Curvature Dipole in Time-Reversal Invariant Materials. Physical Review Letters 115, 216806 (2015).