Giant Spin Hall Effect in AB-Stacked $MoTe_2/WSe_2$ Bilayers

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Primary CNF Tools Used: Zeiss Supra SEM, Nabity Nanometer Pattern Generator System (NPGS), SC4500 Odd/Even-Hour Evaporator, Autostep i-line Stepper, Hamatech Wafer Processor Develop, Heidelberg Mask Writer - DWL2000, Photolithography Spinners, Dicing Saw - DISCO

PHYSICS & NANO-STRUCTURE PHYSICS

Abstract:

The spin Hall effect (SHE) [1,2], in which an electrical current generates a transverse spin current, plays an important role in spintronics for the generation and manipulation of spin-polarized electrons. The phenomenon originates from spin-orbit coupling. In general, stronger spin-orbit coupling favors larger SHEs but shorter spin relaxation times and diffusion lengths. Achieving large SHEs and long-range spin transport simultaneously in a single material has remained a challenge [3]. Here we demonstrate a giant intrinsic SHE that coexists with ferromagnetism in TMD moiré bilayers by direct magneto optical imaging. We also observe long-range spin Hall transport and efficient non-local spin accumulation limited only by the device size (about 10 μm). Our results demonstrate moiré engineering of Berry curvature and electronic correlations for potential spintronics applications.

Summary of Research:

In this study, we explore the intrinsic SHE in AB-stacked $MoTe_2/WSe_2$ bilayers (where the two monolayer crystals are twisted by about 180° and a moiré pattern with a period of about 5 nm due to the lattice mismatch is formed) [4]. The SHE, critical for spintronics, is typically enhanced by strong spin-orbit coupling, but the strong spin-orbit coupling also tends to shorten the spin relaxation times and diffusion lengths. It is therefore challenging to achieve large SHEs and long-range spin transport in a single material. We demonstrate that by using moiré engineering, these properties can be achieved simultaneously. We observe spin accumulation on transverse sample edges that nearly saturates the spin density under moderate electrical currents with density < 1 A/m. We also observe long-range spin Hall transport, as demonstrated by the extended spin current distribution profile. The giant SHE is observed near the interaction-driven Chern insulating state (with one hole per moiré unit cell) and emerges after the quantum anomalous Hall (QAH) breakdown and at low temperatures. Our results highlight the potential of moiré engineering for creating Berry curvature hotspots and controlling electronic correlations. The demonstration of giant SHEs in the same material platform as many reported exotic quantum many-body phenomena opens exciting opportunities for gate-defined lateral heterostructure quantum devices.

Figure 1 is the typical setup for spin Hall effect measurements. A bias current along the x-axis induces a spin Hall current along the y-axis. We fabricated dual-gated AB-stack $MoTe_2/WSe_2$ devices using the reported layer-by-layer dry-transfer technique [5]. Few-layer graphite and hexagonal boron nitride (hBN) are used as the gate electrode and gate dielectric, respectively, in both the top and bottom gates. We first deposited 5 nm Pt contacts on the bottom gate hBN by standard electron-beam lithography and evaporation. We then performed another step of electron-beam lithography and metallization to deposit 5 nm Ti/40-nm Au which connects the thin Pt contacts on hBN to pre-patterned electrodes on the Si substrate.

We transferred the $MoTe_2/WSe_2$ moiré bilayers on top of the hBN layer such that the Pt electrodes are in direct contact with the $MoTe_2/WSe_2$ moiré. Figure 1b shows an optical microscope image of a multi-terminal Hall bar device. The scale bar represents 5 μm.

Figure 2 shows the giant spin accumulation and QAH breakdown. Bias current-dependent MCD images at 6 K (Figure 2a) and 1.6 K (Figure 2b) were taken at the center of the QAH region in the filling-displacement phase diagram. The black dashed lines mark the sample boundaries, and the arrows show the bias current direction. Zero-bias spontaneous MCD is observed only at 1.6 K. The high-bias MCD images, which consist of two domains, are nearly identical for 1.6 K and 6 K. To analyze the interplay between the SHE and the Chern insulator state, we plot the current dependence of edge MCD from two points (P1 and P2) at 1.6 K and 6 K (top) and R_{xx} and R_{xy} at 1.6 K (bottom) in Figure 2c. QAH breakdown is observed near 0.5 μA at 1.6 K (the horizontal dashed line marks the resistance quantum). Concurrently, the MCD at P1 switches sign at the QAH breakdown whereas that at P2 increases gradually and saturates. These results suggest that the SHE dominates after the QAH breakdown with increasing bias current.

Figure 3 shows doping dependent non-local spin Hall transport. In this case, we bias the current between two Hall probes to allow for a longer spin propagation channel. The system supports long range spin transport, as evidenced by the MCD images (Figure 3a), MCD line profile (Figure 3b) and the corresponding spin Hall current density (Figure 3c) at varying filling factors (taken at the grey line in Figure 3a). Spin current J_s is normalized to the value at the current path centerline at 3 μm (vertical dashed line). Non-local spin Hall transport and spin accumulation far away from the current path centerline are most significant at lattice filling factor $v = 1$ for holes.

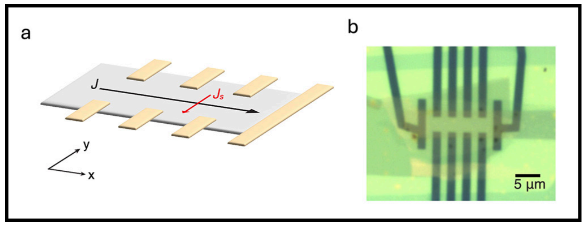

Figure 1: a, Schematic of the spin Hall effect measurements. b, Optical microscope image of a dual-gated device. The scale bar is 5 µm.

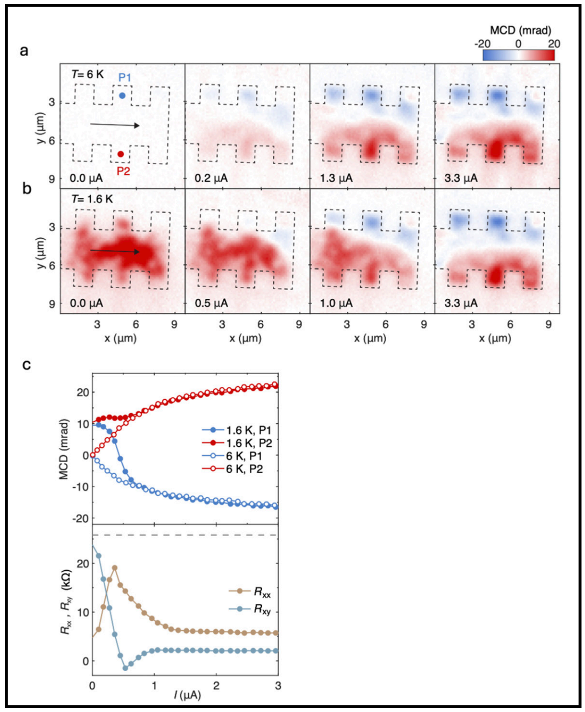

Figure 2: a,b MCD images at varying bias currents at 1.6 K (a) and 6 K (b). c, Bias current dependence of edge spin accumulation and interplay with quantum anomalous Hall breakdown.

Conclusions and Future Steps:

We observe a giant SHE and long-range spin transport in AB-stacked $MoTe_2/WSe_2$ moiré bilayers via MCD imaging. The SHE-induced magnetization nearly saturates spin density under moderate biases. The effect is driven by intrinsic Berry curvature at the Chern insulating state. The effect is the strongest at $v = 1$ due to the Berry curvature hot spots and likely a long spin relaxation time, highlighting the potential for spintronics application and advanced quantum devices.

References:

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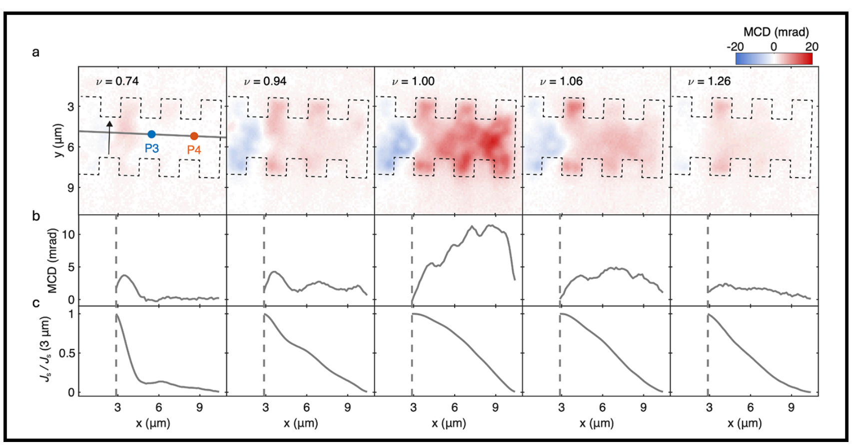

Figure 3: Filling dependence of non-local spin transport. MCD images (a) MCD line profile (b) and the corresponding spin Hall current density (c) at varying filling factors.