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Spintronics in 2D Materials

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Abstract

Two-dimensional (2D) materials provide an exciting platform for spintronics, which started with the demonstration of spin transport in graphene with record long spin diffusion lengths at room temperature. The recent advent of van der Waals stacking of vertical heterostructures has changed the landscape of the field in many ways. I will discuss three key advances including the spin-valley-coupled spin transport, opto-valleytronic spin injection, and room temperature ferromagnetism in monolayer magnets.

1. Spin-Valley-Coupled Spin Transport in Bilayer Graphene

We report the discovery of a strong and tunable spin lifetime anisotropy with excellent out-of-plane spin lifetimes up to 7.8 ns at 100 K in dual-gated bilayer graphene [1]. Remarkably, this realizes the manipulation of spins in graphene by electrically-controlled spin-orbit fields, which is unexpected due to graphene's weak intrinsic spin-orbit coupling (~12 μeV). We utilize both the in-plane magnetic field Hanle precession and oblique Hanle precession measurements to directly compare the lifetimes of out-of-plane vs. in-plane spins. We find that near the charge neutrality point, the application of a perpendicular electric field opens a band gap and generates an out-of-plane spin-orbit field that stabilizes out-of-plane spins against spin relaxation, leading to a large spin lifetime anisotropy (defined as the ratio between out-of-plane and in-plane spin lifetime) up to ~12 at 100 K. Figure 1 illustrates the extracted spin lifetimes for in-plane spins, out-of-plane spins, and their lifetime ratio as a function of carrier density (n) and applied vertical electric field (D_{app}). These clearly show the creation of spin lifetime anisotropy by the applied field. This intriguing behavior occurs because of the unique spin-valley coupled band structure of bilayer graphene. Our results demonstrate the potential for highly tunable spintronic devices based on dual-gated 2D materials.

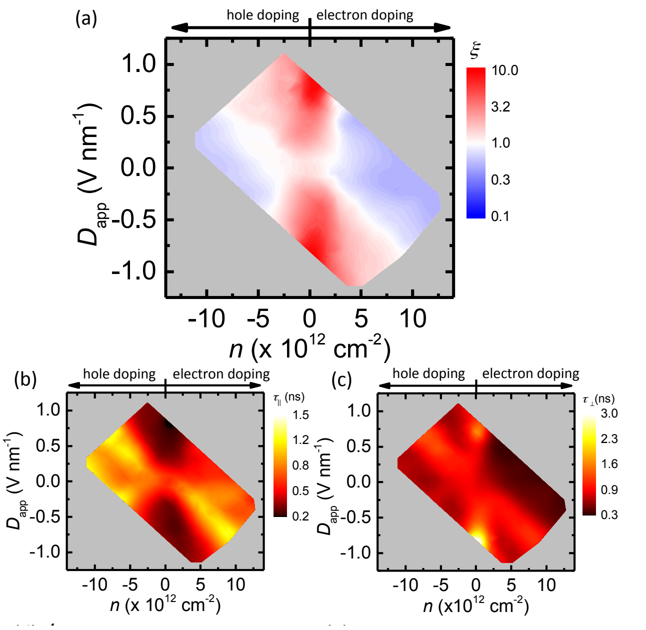

Fig. 1. Electric field (D_{app}) and carrier density (n) dependence of (a) spin lifetime anisotropy ($\xi = \tau_{\perp}/\tau_{\parallel}$), (b) in-plane spin lifetime ($\tau_{\parallel}$), and (c) out-of-plane spin lifetime ($\tau_{\perp}$).

2. Opto-Valleytronic Spin Injection in MoS_2/Graphene Hybrid Spin Valves

2D materials provide a unique platform for spintronics and valleytronics due to the ability to combine vastly different functionalities into one vertically-stacked heterostructure, where the strengths of each of the constituent materials can compensate for the weaknesses of the others. Graphene has been demonstrated to be an exceptional material for spin transport at room temperature, however it lacks a coupling of the spin and optical degrees of freedom. In contrast, spin/valley polarization can be efficiently generated in monolayer transition metal dichalcogenides (TMD) such as MoS_2 via absorption of circularly-polarized photons, but lateral spin or valley transport has not been realized at room temperature. Here, we fabricate monolayer MoS_2/few-layer graphene hybrid spin valves and demonstrate, for the first time, the opto-valleytronic spin injection across a TMD/graphene interface [2]. Figure 2 illustrates the experimental geometry and the Hanle spin signal that verifies the opto-valleytronic spin injection process. We observe that the magnitude and direction of spin polarization is controlled by both helicity and photon energy. In addition, Hanle spin precession measurements confirm optical spin injection, spin transport, and electrical detection up to room temperature. Finally, analysis by a one-dimensional drift-diffusion model quantifies the optically injected spin current and the spin transport parameters. Our results demonstrate a 2D spintronic/valleytronic system that achieves optical spin injection and lateral spin transport at room temperature in a single device, which paves the way for multifunctional 2D spintronic devices for memory and logic applications.

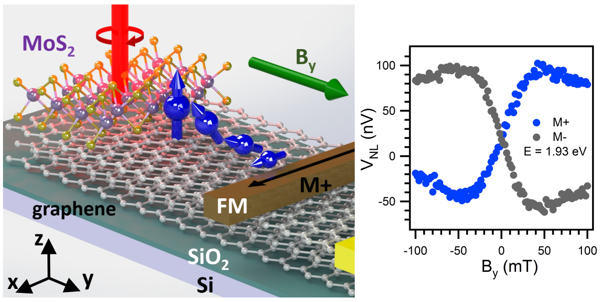

Fig. 2. Opto-valleytronic spin injection, which consists of optical injection into MoS_2, transfer of spin into graphene, and the subsequent detection by ferromagnetic electrodes. The data shows the Hanle spin precession as a function of in-plane magnetic field for the two different magnetization orientations of the ferromagnet's magnetization.

3. Room Temperature Ferromagnetism in Monolayer $MnSe_2$ Epitaxial Films

Monolayer van der Waals (vdW) magnets provide an exciting opportunity for exploring 2D magnetism for scientific and technological advances, but the intrinsic ferromagnetism has only been observed at low temperatures. Here, we report the observation of room temperature ferromagnetism in manganese selenide ($MnSe_x$) films grown by molecular beam epitaxy (MBE) [3]. Magnetic and structural characterization provides strong evidence that in the monolayer limit, the ferromagnetism originates from a vdW manganese diselenide ($MnSe_2$) monolayer, while for thicker films it could originate from a combination of vdW $MnSe_2$ and/or interfacial magnetism of α-MnSe(111). Magnetization measurements of monolayer $MnSe_x$ films on GaSe and $SnSe_2$ epilayers (Figure 3) show ferromagnetic ordering with large saturation magnetization of ~ 4 Bohr magnetons per Mn, which is consistent with density functional theory calculations predicting ferromagnetism in monolayer 1T-$MnSe_2$. Growing $MnSe_x$ films on GaSe up to high thickness (~ 40 nm) produces α-MnSe(111), and an enhanced magnetic moment (~ 2x) compared to the monolayer $MnSe_x$ samples. Detailed structural characterization by scanning transmission electron microscopy (STEM), scanning tunneling microscopy (STM), and reflection high energy electron diffraction (RHEED) reveal an abrupt and clean interface between GaSe(0001) and α-MnSe(111). In particular, the structure measured by STEM is consistent with the presence of a $MnSe_2$ monolayer at the interface. These results hold promise for potential applications in energy efficient information storage and processing.

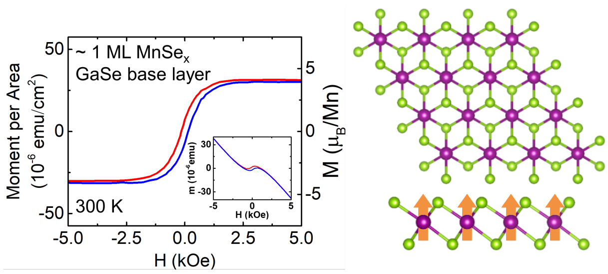

Fig. 3. Room temperature magnetic hysteresis loop of monolayer manganese selenide films.

Acknowledgements

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