Spin Tunnel Field-Effect Transistors Based on Two-Dimensional van der Waals Heterostructures

CNF Project Number: 2633-18

Principal Investigator(s): Jie Shan, Kin Fai Mak

User(s): Lizhong Li, Shengwei Jiang

Affiliation(s): Laboratory of Atomic and Solid State Physics, Applied and Engineering Physics; Cornell University

Primary Source(s) of Research Funding: National Science Foundation under award DMR-1807810 for the sample and device fabrication, the Office of Naval Research under award N00014-18-1-2368 for the device characterization, and the Air Force Office of Scientific Research Hybrid Materials MURI under award FA9550-18-1-0480 for optical measurements

Contact: jie.shan@cornell.edu, kinfai.mak@cornell.edu, sj538@cornell.edu, ll646@cornell.edu

Primary CNF Tools Used: Autostep i-line stepper, Hamatech wafer processor develop, Heidelberg mask writer DWL2000, photolithography spinners, SC4500 odd/even-hour evaporator, DISCO dicing saw

Abstract:

Transistors based on control of spin orientations, if realized, can revolutionize modern electronics through the implementation of faster and more energy efficient performance and non-volatile data storage. Recent development in magnetic switching by a gate voltage and magnetic reading by the spin filtering effect in two-dimensional magnets has inspired a new operational principle for spin transistors. In this project, we demonstrate a spin tunnel field-effect transistor based on dual-gated graphene/CrI_3 tunnel junctions.

Summary of Research:

Spin field-effect transistors (FETs) were first proposed by Datta and Das in 1990 [1]. These spin-based devices promise non-volatile data storage and faster and more energy-efficient performance than the current transistors. The original proposal that relies on electric-field-controlled spin precession in a semiconductor channel, faces significant challenges including inefficient spin injection, spin relaxation and spread of the spin precession angle. The recently discovered two-dimensional magnetic insulators [2,3] provide a unique platform to explore new spintronic device concepts. In this project, we develop a tunnel field-effect transistor (TFET) based on few-layer CrI_3 as a magnetic tunnel barrier to achieve spin-dependent outputs that are voltage controllable and reversible.

Figure 1 shows the device structure. It consists of a van der Waals heterostructure of bilayer graphene/bilayer CrI_3/bilayer graphene with top and bottom gates. The vertical tunnel junction utilizes bilayer graphene as the source and drain contacts and bilayer CrI_3 as the magnetic tunnel barrier. The two nearly symmetric gates are made of few-layer graphene gate electrodes and hexagonal boron nitride (hBN) gate dielectrics. The gates tune the Fermi level of the nearest bilayer graphene contact effectively, which modulates the conductance of the junction through resonant tunneling.

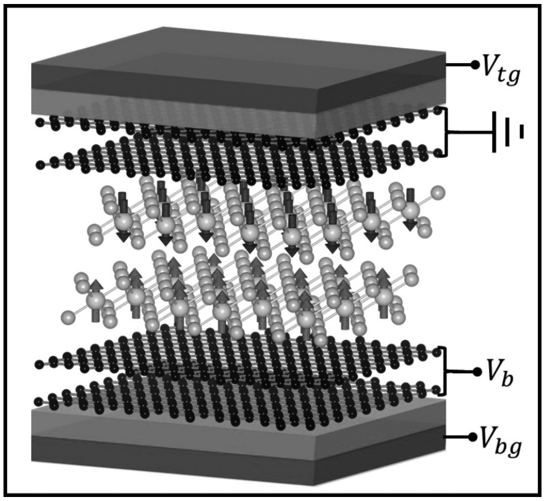

Figure 1: Operational principle of a spin TFET based on gate-controlled spin-flip transition in bilayer CrI_3 and spin filtering in the tunnel junction. Arrows indicate the spin orientation in CrI_3 layers.

The gates can also cause a significant modulation in the tunnel conductance by inducing a spin-flip transition in bilayer CrI_3 by an electric field or through electrostatic gating [4-6]. The conductance is high (low) when the spins in the two layers are aligned (misaligned) due to the spin-filtering effect [7,8]. A spin-TFET action is realized

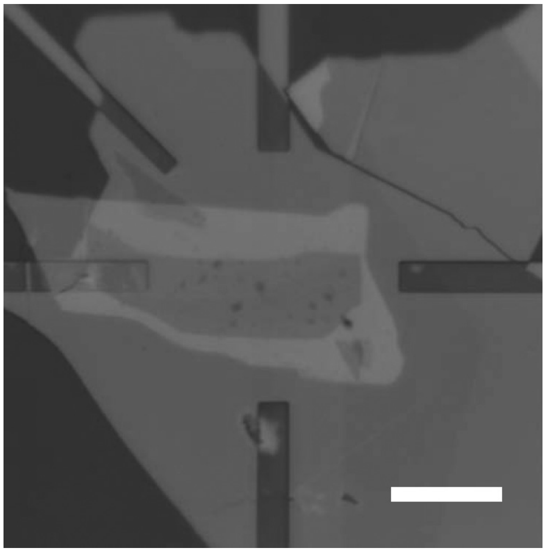

Figure 2: Optical images of a van der Waals heterostructure device deposited on pre-patterned electrodes.

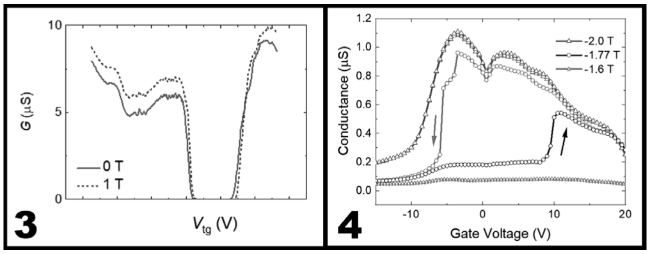

Figure 3, left: Gate dependence of the tunnel conductance in a bilayer CrI_3 device under an out-of-plane magnetic field of 0 T and 1 T [6]. Figure 4, right: Tunnel conductance of a TFET with a four-layer CrI_3 tunnel barrier is repeatedly switched by gating under a constant magnetic bias of -1.77 T. The top and bottom gate voltages are identical, and their sum is shown in the horizontal axis [6]. Results under -2.0 T and -1.6 T (corresponding to the barrier in the ferromagnetic and antiferromagnetic state, respectively) are included for comparison.

through electrical switching of spins in the magnetic tunnel barrier.

Figure 2 is an optical image of a typical device. The Ti/Au electrodes were first patterned on Si/SiO_2 substrates by photolithography and metal evaporation. Atomically thin samples of CrI_3, hBN, and graphene were first exfoliated from their bulk crystals onto silicon substrates covered with a 300 nm thermal oxide layer. The selected thin flakes of appropriate thickness and geometry were then picked up one-by-one by a stamp consisting of a thin layer of polycarbonate on polydimethylsiloxane. The complete stack was then deposited onto the substrates with pre-patterned Au electrodes.

An ambipolar transistor behavior with a zero conductance (i.e. off) state is observed for graphene tunnel junctions (solid line, Figure 3). This is a consequence of a sizable band gap opened in both bilayer graphene contacts by a built-in interfacial electric field from the asymmetric hBN/bilayer graphene/bilayer CrI_3 structure.

The TFET output is dependent on the magnetic state of the tunnel barrier. Under a vertical magnetic field of 1 T (dashed line, Figure 3), bilayer CrI_3 switches from an interlayer antiferromagnet to a ferromagnet. The gate dependence of the conductance shifts towards a slightly larger gate voltage, corresponding to a shift in the energy level alignment in the tunnel junction. The tunneling conductance increases over a large doping range.

We demonstrate the spin TFET action, i.e. control of the tunnel conductance by electrically switching the magnetic state of CrI_3. To minimize the trivial conductance, change due to electrostatic doping, we choose a range of gate voltage, where the conductance is weakly gate dependent. Figure 4 shows the result for a 4-layer CrI_3 device under a constant magnetic bias (-1.77 T), which is slightly above the spin-flip transition [9]. The gate voltage can repeatedly alter the TFET between a high and a low conductance state. As a reference, we also include the conductance under a bias magnetic field much above or below the spin-flip transition.

A relative change of ~ 400% in the tunnel conductance with a large hysteresis has been achieved through gating. The switching is originated from a gate-dependent spin-flip transition field.

In conclusion, a new type of spin transistors is achieved, which relies on the spin filtering effect to inject and detect spin, and electrical switching of the magnetization configurations in the tunnel barrier.

References:

[1] Datta, S., and Das, B. Applied Physics Letters 56, 665 (1990).

[2] Huang, B., et al. Nature 546, 270 (2017).

[3] Gong, C., et al. Nature 546, 265-269 (2017).

[4] Jiang, S., Shan, J., and Mak, K. F. Nature Materials 17, 406 (2018).

[5] Jiang, S., Li, L., Wang, Z., Mak, K. F., and Shan, J. Nature Nanotechnology 13, 549 (2018).

[6] Huang, B., et al. Nature Nanotechnology 13, 544 (2018).

[7] Song, T., et al. Science 360, 1214-1218 (2018).

[8] Klein, D. R., et al. Science 360, 1218-1222 (2018).

[9] Jiang, S., Li, L., Wang, Z., Shan, J., and Mak, K. F. Nature Electronics 2, 159 (2019).