VALLEYTRONICS

Magnetization without polarization

A pure electrical generation of magnetization through electrons' valley magnetic moment has been observed in strained two-dimensional semiconductor.

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In solids, the crystalline structure can endow electron a valley degree of freedom, which labels the degenerate energy minima in momentum space. The possibility for varieties of dynamic controls on valley has led to the concept of valleytronics[1], which aims at using valley, in addition to charge and spin, to carry and process information. Now, writing in Nature Materials, Jieun Lee and colleagues[2] have reported experimental evidences for a valley magnetoelectric effect in strained MoS_2 monolayer, where charge current generates bulk magnetization through valley. The finding implies a new possibility for integrating valleytronic controls with magnetic information storage.

MoS_2 is a member of the semiconducting transition metal dichalcogenides (TMD) family in which the monolayers all host similar valley physics[3]. Electrons and holes both have a pair of valleys centered at the K and -K corners of the hexagonal Brillouin zone. As a manifestation of the Berry phase of the electronic wave function[4], carriers in a 2D hexagonal lattice acquire an orbital magnetic moment, which points out of the 2D plane in opposite directions at K valley and its time-reversal counterpart -K (Fig. 1a) [5,6]. Such a magnetic moment signifies valley state of carrier, just like the one associated with spin, and thus makes possible interplay of valley with magnetism. Unlike the constant spin moment, the magnitude of the valley magnetic moment depends on carrier's momentum (Fig. 1a). This leads to a new way to link valley with magnetization.

As the analog of spin polarization, valley polarization refers to the population unbalance between the valleys (Fig. 1a). Through the valley magnetic moment arising from Berry phase effect, valley polarization leads to the magnetization of the material. Interestingly, in the absence of valley polarization, valley magnetization can still arise from the manipulation of carriers' momentum distribution as schematically depicted in Fig. 1b, because valley magnetic moment has the momentum dependence. Lee and co-workers demonstrated one such possibility from the joint effect of current and strain[2].

The three-fold rotational symmetry of the MoS_2 hexagonal lattice requires the valley moment distribution to have its maxima at the valley center (Fig. 1a). When strain breaks this rotational symmetry, the distribution of valley magnetic moment is displaced in momentum space with respect to the valley centers[7], while time reversal symmetry dictates the displacement at K valley is opposite to that at -K (Fig. 1b). In a charge current, the Fermi pockets at K and -K, both shifted along the current direction (c.f. solid circles in Fig. 1b), can enclose different amount of magnetic moment. A net magnetization is thus associated with this nonequilibrium distribution even though the population remains balanced between the two valleys. This magnetization is linearly proportional to the charge current projection along the displacement of valley magnetic moment distribution by strain ($\mathbf{k}_0$ in Fig. 1b).

In the experiments, valley magnetization of either type, from valley polarization or without valley polarization, can be detected using the Kerr rotation microscopy, a standard technique to image spin magnetization. It works equally well for valley magnetization, thanks to the intrinsic connection of valley magnetic moment to circular dichroism[6] that underlies Kerr rotation, a change in light polarization upon reflection. In an earlier work from the same group[8], Kerr rotation microscopy was used to image the valley polarization accumulated at the edges of bilayer MoS_2 by the valley Hall current, the latter being another manifestation[5] of the Berry phase effect that has led to valley magnetic moment. In the work by Lee and colleagues[2], the valley Hall effect in monolayer MoS_2 is also evidenced by the opposite Kerr rotation signal at the two edges. The new finding here is a much stronger Kerr rotation signal observed nearly uniformly over the entire monolayer bulk when, and only when current and strain are both present as shown in Fig. 1c. They examined the dependences of the Kerr rotation angle on the magnitude of bias current, and on the current and strain directions with respect to the crystalline axis[2], which consistently point to the valley magnetization in the valley-unpolarized nonequilibrium momentum distribution.

It is worth pointing out that the two types of valley magnetization have distinct relaxation dynamics. The one associated with valley polarization decays through the intervalley scattering (Fig. 1a), which is typically slow due to the large separation of valleys in momentum space. The magnetization without valley polarization decays through the much faster intravalley momentum relaxation (Fig. 1b), and disappears instantaneously when charge current is switched off. Nevertheless, this magnetoelectric effect that is shown to persist at room temperature provides a practical mechanism for charge-magnetization conversion in valleytronic devices. One can envision van der Waals heterostructure devices composed of semiconducting TMD monolayer and ferromagnetic monolayer such as CrI_3 [9], where the lateral current flow in TMD channel can exert a torque, via the induced valley magnetization, to switch the proximity ferromagnetic layer in magnetic memories.

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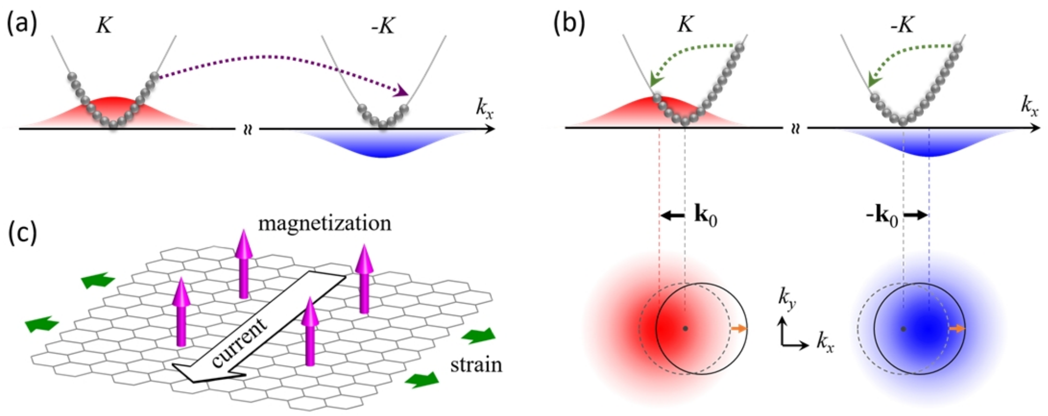

Figure 1 Magnetization with and without valley polarization. a, Magnetization from valley polarization. Shaded curve denotes the distribution of valley magnetic moment as a function of momentum. **b,** Magnetization without valley polarization. The distribution of valley magnetic moment has a displacement $\mathbf{k}_0$ ($-\mathbf{k}_0$) from the valley center at K (-K), due to strain. In equilibrium, the magnetization remains zero as the Fermi pockets at K and -K (dashed circles) enclose the same amount of magnetic moment with opposite sign. In a charge current, the shifted Fermi pockets (solid circles) enclose different amount of magnetic moment at the two valleys, giving rise to a net magnetization. The two types of valley magnetization in **a** and **b** decay through intervalley and intravalley scattering respectively (dotted arrows). **c.** Schematic of current induced valley magnetization in the strained monolayer.