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Spin-valley Hall transport induced by spontaneous symmetry breaking in half-filled zero Landau level of bilayer graphene

Intrinsic Hall conductivity, emerging when chiral symmetry is broken, is at the heart of future low energy consumption devices. A symmetry breaking state is also induced by electronic correlation even for the centro-symmetric crystalline materials. However, generation of non-dissipative charge neutral current by Hall conductivity induced by such spontaneous symmetry breaking is experimentally elusive. In this presentation, we report intrinsic Hall conductivity and generation of a non-dissipative charge neutral current in a spontaneous antiferromagnetic state of zero Landau level of bilayer graphene.

It is known that gap opens at v=0 of monolayer and bilayer graphene due to electron interaction. This state shows unique properties such as the absence of edge channels, phase transition driven by a tilted magnetic field or a perpendicular electric field[1], and the recently observed long-range spin transport[2,3]. Its nature is thought to be layer antiferromagnetic (LAF) state, where spins tend to align ferromagnetically due to the exchange interaction within each layer and antiferromagetically between the layers (Fig.1a)[4-6]. Because opposite spins occupy opposite layers, sign of effective mass term depends on the spin [4,7]. So instead of the conventional valley current, spin-valley current, which is defined as the difference of valley current between the spins, is expected to flow (fig.1b). This theoretically predicted spin-valley Hall effect [7] has been experimentally elusive.

In this study, we investigated nonlocal transport in the LAF state of bilayer graphene encupsulated by hexagonal Boron Nitride and obtained two evidences that the nonlocal transport voltage is caused by the spin-valley Hall effect. They are enhancement of nonlocal transport for the LAF state in gate voltage dependence and cubic scaling relationship between the local and nonlocal resistance similarly to the previous experiments on the valley Hall effect [8,9].

First we show gate voltage dependence. Figure 2a is the top gate and back gate voltage dependence of R_L (local resistance). When the magnetic field of 2 T is applied, a local maximum appears around the D=0, n=0 point similarly to the previous report [1], indicating the development of LAF insulating state. This state becomes more robust for the higher magnetic field. Then we performed nonlocal transport measurement for this state. Figure 2b shows gate voltage dependence of R_NL (nonlocal resistance) under the magnetic field of 2 T and 4 T. R_NL increases around D=0, n=0, where R_L also increases. The value of R_NL is much larger than the expected value for the trivial classical current diffusion.

Next, we turn to the relationship between the R_L and R_NL obtained by changing the magnetic field and temperature (see Figure 3). We find that all data points lie on a single curve of the cubic scaling. This scaling relationship is explained by conductance matrix model under the assumption of $\sigma_{xx} > \sigma_H$ and is common for

nonlocal transport mediated by non-dissipative charge neutral current. Fig. 3 insets show bias voltage dependence of the differential conductance, and the gap size evaluated from it. Note energy scale of the measured temperature (1.7~ 32 K) is smaller than the gap size. In the other sample with higher resistance at the CNP, we found linear scaling for Rxx > 90 kΩ expected for $\sigma_{xx} < \sigma_H$.

Our demonstration evidences the spin-valley Hall effect induced by the spontaneous symmetry breaking driven by the electronic correlation. This highly correlated state is also a spin-valley-coupled state, and will make electrical generation of a spin current in non-magnetic graphene via coupling of spin and valley possible. We will also present the experimental progress of this new attempt.
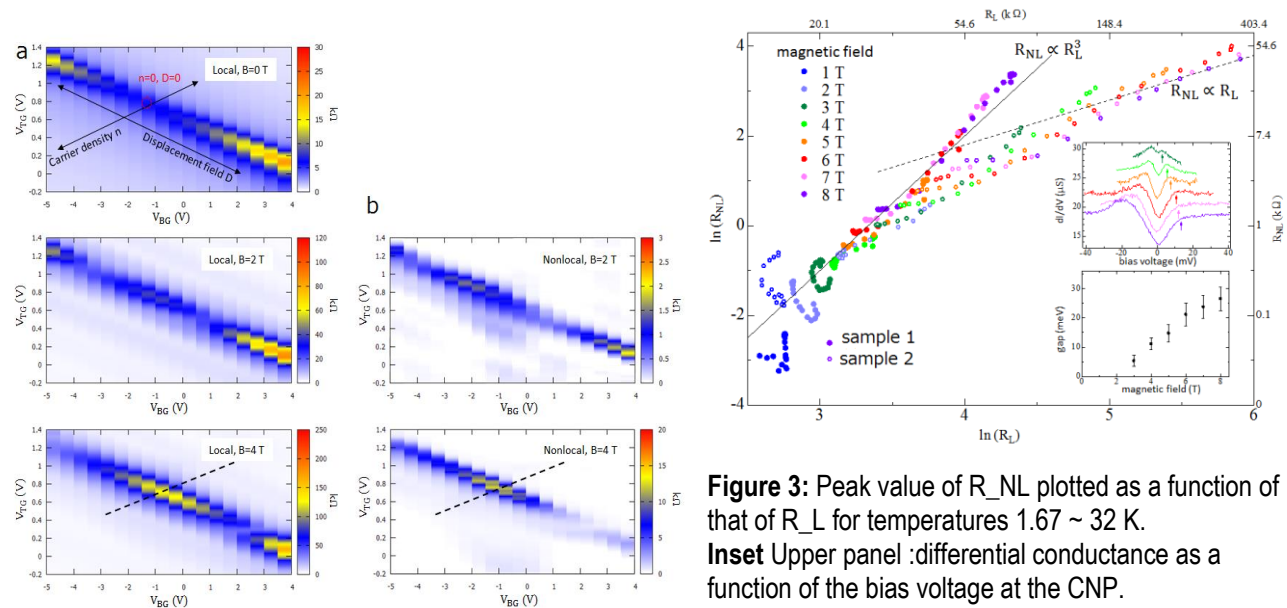
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Figures
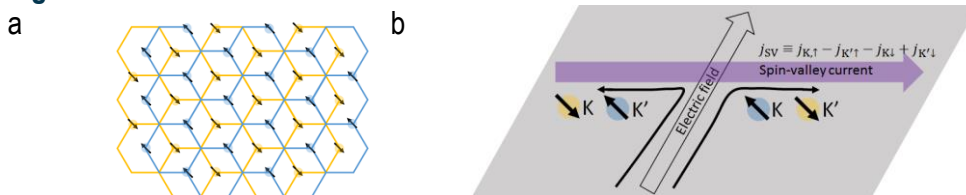
Figure 1: a, Spin and sublattice configuration of the LAF state at the half-filled v=0 Landau level in bilayer graphene. Blue and yellow hexagons are the lattices of top and bottom layers, respectively.
b, Schematic description of the spin-valley Hall effect and definition of the spin-valley current

Figure 3: Peak value of R_NL plotted as a function of that of R_L for temperatures 1.67 ~ 32 K.
Inset Upper panel :differential conductance as a function of the bias voltage at the CNP.
Lower panel :gap size extracted from the upper panel.

Figure 2:
Gate voltage dependence of the R_L (a) and R_NL (b)
 at T=1.67K