Splitting of the zero-energy Landau level in epitaxial graphene on SiC

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Zero-energy states in high fields in graphene have been widely studied for a variety of physics associated with the lifting of fourfold spin and valley degeneracy using high-mobility samples exfoliated from graphite [1]. For epitaxial graphene on SiC, on the other hand, the ground states at zero energy still remain unexplored, since accessing the charge neutrality point without deteriorating sample qualities has been difficult. Using top-gated devices in both Hall-bar and Corbino geometries, we demonstrate lifting of spin/valley degeneracy in epitaxial graphene at high fields, which manifests as a double peak in longitudinal conductivity (σ_{xx}) around $\nu = 0$. The energy gap associated with the Landau level (LL) splitting is estimated from transport spectroscopy that we recently developed [2] as well as from temperature (T) dependence of longitudinal resistance R_{xx}.

The Hall-bar sample with width 40 μm and length 200 μm was fabricated from epitaxial graphene grown on 6H-SiC(0001). At T = 8 K, R_{xx} at $\nu = 0$ increases almost linearly with B, whereas at T = 1.6 K, it rapidly increases with B [Fig. 1(a)], indicating strongly insulating behavior at high B. Converting the measured R_{xx} and Hall resistance, the latter fluctuating around zero, into σ_{xx} reveals a double peak with a minimum at $\nu = 0$, signaling the splitting of the zero-energy LL [Fig. 1(b) top]. At $\nu = 0$, σ_{xx} is thermally activated, which corroborates the insulating behavior of the $\nu = 0$ state. Direct measurement of σ_{xx} using a Corbino device finds LL splitting of similar magnitude.

We estimated the energy gap Δ at $\nu = 0$ in two ways. First, the T dependence of R_{xx} at 16 T can be well fitted by $R_{xx} \sim \exp(\Delta/2k_BT)$ with the Boltzmann constant k_B [Fig. 1(c)], yielding $\Delta \sim 7$ K at 16 T. Second, we analyzed the trajectories of the σ_{xx} peaks mapped vs. V_g and B. The mapping reveals parabolic, instead of linear, fan diagram that reflects the relativistic graphene LLs, because, in the presence of high-density interface states, the Fermi energy of graphene varies in proportion to V_g [2]. We find that at high B the positions of the split σ_{xx} peaks are quite close to those of $\nu = \pm 1$ [Fig. 1(b) bottom]. Analyzing these data gives the upper bound of the gap, which can be crudely estimated to be 15 K at 16 T. In the conference, we will discuss the underlying physical mechanism of the $\nu = 0$ gap.

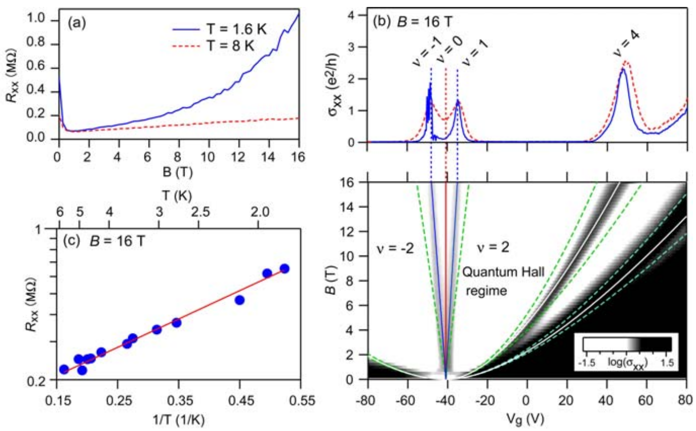

Fig. 1(a) R_{xx} at $\nu = 0$ vs. B at T = 1.6 and 8 K. (b) Top: σ_{xx} vs. V_g at B = 16 T. Bottom: σ_{xx} vs. V_g and B. Solid lines indicate ν = 0, ±1, ±4, and 8, and dashed ones mark borders between integer and non-integer fillings. (c) R_{xx} at $\nu = 0$ vs. $1/T$ at B = 16 T. The solid line shows Arrhenius equation with Δ = 7 K.

[1] A. F. Young *et al.*, Nat. Phys. **8**, 553 (2012). [2] K. Takase *et al.*, Phys. Rev. B **86**, 165435 (2012).