Divergence of Resistance at Dirac Point of Graphene in Intense Field

J. G. Checkelsky, Lu Li and N. P. Ong (Princeton Univ.)

Introduction

The high-field ground state of monolayer graphene has been of strong interest following the observation of quantized Hall effect by Geim et al. and by Kim et al. In an intense field H, the electronic states are quantized into Landau Levels (LLs) which are nominally 4-fold degenerate (reflecting the valley and spin indices). The interesting question is what happens when the chemical potential μ is tuned to the Dirac Point. With increasing H, the exchange energy increases as $\sqrt{H}$. The 4-fold degeneracy of the n=0 LL is expected to be lifted in a many-body state with spontaneous broken symmetry involving either the spin degrees or valley degrees (the quantum Ferromagnet state). This leads to a bulk gap. However, some theories have proposed that counter-propagating edge states remain at large H. Because these edge states carry current, the system remains metallic to intense fields despite the bulk gap. We have measured the resistance R_0 at the Dirac Point in fields up to 35 T, and at temperatures T down to 0.3 K. Instead of persistent metallic conduction, we find that at a critical field H_c, the system becomes insulating [1, 2]. By systematically decreasing the Joule heating to levels below 3 fW, we show that R_0 undergoes a steep increase to values as large as 40 MΩ.

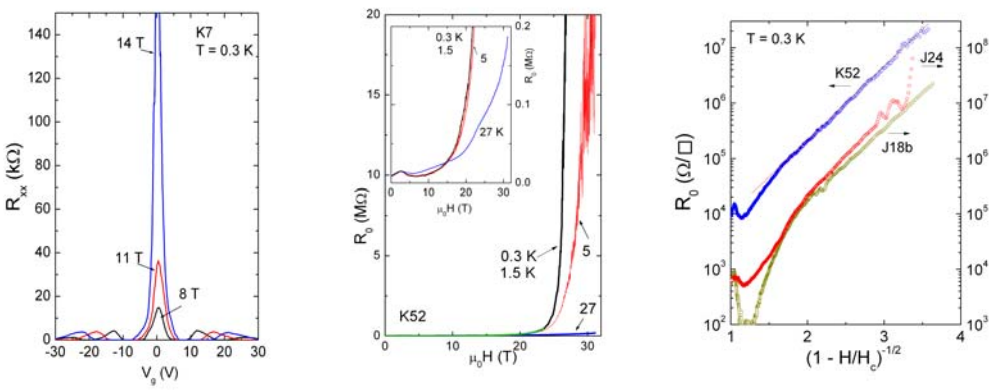

Figure 1 (Panel a, left). Traces of the longitudinal resistance R_{xx} vs. (shifted) gate voltage V_g in fixed field H. As H increases to 14 T, the peak R_0 at the Dirac Point increases sharply to 140 kΩ [1]. Panel b (middle) shows the steep increase in R_0 with H on the MΩ scale. The inset shows the increase in R_0 in expanded scale [2]. Panel c (right) displays the linear behavior of R_0 when plotted in semilog scale vs. the function $(1-h)^{-1/2}$ in 3 samples. The linear behavior (which extends over 3 decades) is consistent with the KT divergence of correlation length [2].

Results and Discussion

Figure 1 summarizes some of our results. In earlier measurements [1] up to 14 T, we found that R_0 (the value of R_{xx} at the Dirac Point) shows an incipient increase at our lowest T (0.3 K). As shown in Fig. 1a, as H increases from 8 to 11 and 14 T, R_0 (peak at n = 0 LL) increases rapidly whereas the peaks at the $n = \pm 1$ LLs remain near the quantum resistance h/e^2. To reduce the Joule self-heating below the pW level, we repeated the measurements [2] using a 4-probe voltage-regulated technique that dissipates less than 3 fW at 0.3 K. This has allowed us to follow the divergence in R_0 to values of 40 MW. As shown in Fig. 1b (main panel), R_0 undergoes a sharp increase near 25 T, exceeding 20 MW at 0.3 K. The inset shows an expanded view of the increase at several T. Remarkably, the increase of R_0 vs. H is much steeper than an exponential function. We have found that it fits the expression for the divergence of the Kosterlitz-Thouless (KT) correlation length, $R_0 \sim \exp[b(1-h)^{1/2}]$ where the reduced field $h = H/H_c$, with H_c a critical field. Figure 1c shows the fit to this expression over 3 decades in R_0 in 3 samples [2].

Acknowledgements

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References

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