High-field magneto-transport at charge neutrality point in monolayer graphene

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Abstract. We have investigated the magneto-transport around filling factor $\nu=0$ in monolayer graphene sheet. Zero Hall plateau of Hall conductivity and minimum of longitudinal conductivity have been clearly observed despite the highly fluctuated behaviour of magneto-resistance above 10 T. These phenomena can be understood by the transport of counter-propagating electron and hole edge states at the charge neutrality point. We tried to explain the origin of remarkable fluctuations in magneto-resistance by the energy relaxations among the counter-propagating edge channels.

1. Introduction
Recently, the unique phenomena in a monolayer graphene around the charge neutrality point (CNP) have been reported [1, 2]. In the monolayer graphene, the lowest Landau level (LL) appears at the CNP corresponding to the zero energy in magnetic fields. In high magnetic fields, the lowest LL shows spin splitting and the confinement potential at the edge of graphene sheet splits the remaining valley degeneracy. Hence, the two band branches due to the valley splitting at the edge can be regarded as an electron-like and a hole-like edge states which are formed only in the lowest LL. In this case, the fluctuated magneto-resistance is observed, which is similar behavior reported in the electron-hole coexistence system, such as an InAs/GaSb type-III quantum well (QW) [3]. In the InAs/GaSb QW, the observed highly fluctuated magneto-resistance was explained by the energy relaxation of current carrying electron and hole edge channels. Motivated by the analogy of the properties of the electron transport, we have discussed the origin of the fluctuations in the magneto-resistance at the CNP in the monolayer graphene.

2. Sample
Monolayer graphene sheet was made from Kish graphite (Covalent material co.) by using a micro-mechanical cleavage method as shown in Ref. [4], and was mounted on an n-doped Si/SiO$_2$ (280 nm) substrate, which was used as a back-gate to control the carrier density by applying gate voltage ($V_g$). The annealing process for cleaning graphene sheet was omitted. A Hall bar shaped sample with Au/NiCr electrodes was fabricated by using an electron beam lithography, as shown in Fig. 1(a).

The magneto-transport measurement was performed in a top loading $^3$He-$^4$He dilution refrigerator with a superconducting magnet up to 15 T, by using low frequency (12.5 Hz) ac excitation current of 30 nA. The carrier density $n_c$ can be adjusted from $-2.0\times10^{16}$ (hole) to $8.0\times10^{15}$ (electron) m$^{-2}$ by tuning the back-gate voltage, as shown in Fig. 1(b). The dotted line in Fig. 1(b) is calculated carrier
density with the simple capacitor model of $n_g = \varepsilon_r \varepsilon_0 V_g / t e$, where the dielectric constant $\varepsilon_r$ of SiO$_2$ is 4.2 and $t$ is the thickness of SiO$_2$ layer. The calculated $n_g$ agrees with the measured one, as shown in Fig. 1(b). The typical carrier mobility $\mu$ based on the Drude model was below ~2.0 m$^2$/Vs around the CNP.

3. Results and discussion

Figure 2 (a) shows Hall resistivity ($\rho_{xy}$) and longitudinal resistivity ($\rho_{xx}$) as a function of $V_g$ at $B=4$ T. Half-integer quantum Hall effect (QHE) and Shubnikov de-Haas oscillations corresponding to the filling factor $\nu=\pm2$, 6, 10, 14, which are unique numbers in the monolayer graphene QHE plateaus, are clearly observed. In Fig. 2(b), the analysis of LL index plots at $V_g=\pm8$ and $\pm12$ V pass on the LL index $n=1/2$, which indicates the phase shift due to the Berry’s phase $\pi$.

Next, we focus on the resistivity in higher magnetic field at $B=15$ T and at low temperature $T=0.5$ K, as shown in Fig. 3 (a). The observed $\rho_{xy}$ and $\rho_{xx}$ show remarkable fluctuations around the CNP ($V_g=9.8$ V) corresponding to the filling factor $\nu=0$, and these fluctuations are reproducible. On the other hand, the Hall conductivity $\sigma_{xy}$ and longitudinal conductivity $\sigma_{xx}$ obtained from $\rho_{xy}$ and $\rho_{xx}$ data show the zero Hall plateau of $\sigma_{xy}$ and the minimum of $\sigma_{xx}$, as shown in Fig. 3 (b). The value of $\sigma_{xx}$ minimum and the width of the zero Hall plateau strongly depend on the value of magnetic field.

![Image](74x563 to 514x724)

Fig. 1. (a) The optical microscope image of monolayer graphene sample. (b) Carrier density and mobility as a function of $V_g$ evaluated from the low-field transport. The dotted line is a carrier density $n_g$ calculated from the geometry of the sample.

![Image](107x115 to 506x267)

Fig. 2. (a) Resistivity at $B=4$ T as a function of $V_g$. (b) Landau level index plot of $\rho_{xx}$.
By using the counter-propagating edge (CPE) channel [1], we can explain the relation between Fig. 3(a) and 3(b) with the calculated curves as shown in 3(c) and 3(d). In the CPE channel model, the magneto-transport is influenced by the intra-edge scattering $\gamma$ between two counter-propagating edge channels and the inter-edge scattering rate $g$ through the edge-bulk-edge path. The analysis with the CPE channel model gives the scattering parameters $w\gamma=15$, $gw=1.5$ in our system ($w$: channel width), which roughly agree with ones in ref. [1]. Note that the fluctuation pattern of the magneto-resistance indicates the existence of edge channel branches at the CNP condition, which supports the spin splitting of the lowest LL in the bulk regime.

Fig. 4. The magneto-resistance at (a) $V_g=8$ V(hole), (b) 9.8 V(CNP), and (c) 12 V(electron), measured at 0.5 K. Two lines of $\rho_{xy}$ in (a) are measured in the reversal magnetic fields.
Figure 4 (a)–(c) show the magneto-resistivity $\rho_{xy}$ and $\rho_{xx}$ at the low carrier density condition of $V_g$=8.0, 9.8, and 12.0 V, which correspond to $n_s= -2.4 \times 10^{15}$ (hole), 0.0 (CNP), and $+2.1 \times 10^{15}$ (electron) m$^{-2}$, respectively. Each $\rho_{xy}$ shows small and reproducible fluctuations, and $\rho_{xx}$ drastically increases in high magnetic fields. As shown in Fig. 4 (a), the $\rho_{xy}$ indicates normal behavior with the reversal of magnetic fields; $\rho_{xy}(B) = -\rho_{xy}(-B)$ at $|B|<10$ T, on the other hand, at $|B|>10$ T, the remarkable asymmetry $\rho_{xy}(B) \neq -\rho_{xy}(-B)$ was observed. These fluctuation and asymmetry were observed clearly around the CNP condition and at low temperatures below 1 K.

We tried to understand the fluctuation behavior in the magneto-resistance near the CNP by using the fluctuated edge channel model based on the CPE channel [1] and the concept of electron transport in the electron-hole coexisting type-III QW [3]. Figure 5 shows the schematic cross-sectional view of the LL along the sample width direction. The edge channels in the graphene sheet are expected to be spatially fluctuated (winding) as schematically shown in Fig. 5. The electron scattering rate of the inter-edge channels is enhanced at the overlapping points of counter-propagating edge channels, where the chemical potential for each channel should be equilibrated. The number and the position of the overlapping point of the CPE channels may change with sweeping $V_g$ and/or magnetic fields, since the spatial distribution of edge channels also changes as shown in Fig. 5. Thus the reproducible magneto-resistance fluctuation observed around the CNP condition can be understood by considering the distribution of the potential disorder in the graphene sample and the electron scattering among the overlapping CPE channels due to the potential fluctuation near the sample edge. In the high magnetic fields more than 10 T, the Hall resistance also shows fluctuation and it does not show symmetry (Fig. 4(a)) for magnetic field reversal $\rho_{xy}(B) \neq -\rho_{xy}(-B)$. Moreover, the observed $\rho_{xy}$ deviates remarkably from the normal value estimated from the carrier density. These results are consistent with the electron transport model around the CNP in high magnetic fields, as mentioned above. Around the CNP, the distribution of the electrochemical potential along the sample edge is mainly governed by the energy equilibration among CPE channels due to the potential fluctuation in the graphene sample. So, the measured $\rho_{xy}$ and $\rho_{xx}$ do not show the ‘bulk resistivity’ but show the reproducible fine fluctuations as sweeping $V_g$ and/or $B$.

Finally, we discuss about insulating behavior in $\rho_{xx}$ in high magnetic fields and at low temperature. Figure 6 shows rapid increase from 6 to 200 k$\Omega$ in the resistivity $\rho_{xx}$ with increasing magnetic fields measured at the gate voltage of $V_g$=9.8 V (CNP). The bulk conductivity $\sigma_{xx}$ at the CNP decreases with

![Fig. 5. The schematic explanation of the lowest LL and the edge channels at the CNP. (a) Electron and hole edge states (solid and broken curves) spatially overlap at the CNP(2) by tuning $V_g$. The overlapped CPE channels can be regarded as ‘micro-loop array’ and the adjacent micro-loops are weakly coupled each other at the crossing point of the CPE channels. (b) In the high magnetic fields, the overlapped CPE channels at the CNP are pushed to the sample boundary, where the energy equilibration length of the edge channels may be short.](image)
lowering temperatures below 1 K, and the highly magnetic field dependent gap energy at the CNP was studied by the analysis of temperature dependence of the $\sigma_{xx}$ [5]. Our experimental results also show the insulating behavior of $\rho_{xx}$ at the CNP in high magnetic fields ($|B|>10$ T) which is understood by considering both the decreasing of the residual bulk $\sigma_{xx}$ and the strong energy equilibration in the overlapped CPE channels at the CNP. Note that the energy equilibration in the CPE channels strongly reduces the electron transport through the CPE channels.

We also tried to plot our $\rho_{xx}$ data taken at the CNP with the calculated curve by the theory of Kosterlitz-Thouless (KT) type function (inset of Fig. 6). The observed $\rho_{xx}$ data can be fitted to the KT-type function with the parameter of $B_c=21.4$ T. Similar insulating behavior was reported, in which the possibility of the KT transition at the CNP was discussed [2]. And the origin of KT transition-like behavior [6,7] in the high mobility graphene was also discussed, however, more experimental and theoretical efforts are still needed to understand both the magneto-resistance fluctuation and the field-induced insulating behavior at the CNP in the low mobility samples.

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