Magnetoresistance of Rippled Graphene in a Parallel Magnetic Field

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Abstract. The magnetoresistance of a monolayer graphene in a random magnetic field (RMF) with zero mean has been investigated. The RMF was produced by applying a magnetic field parallel to the graphene plane utilizing ripples. The magnetoresistance has shown the same magnetic field dependence and, unexpectedly, the same carrier density dependence as the conventional two-dimensional electron systems in random magnetic fields. The relation between the characteristic length of ripples and the magnitude of the magnetoresistance is discussed.

1. Introduction
Since the discovery of graphene,[1] numerous theoretical and experimental papers studying the novel properties of graphene have been published.[2, 3] Among these studies, it is well known that there are ripples in a graphene suspended in space or placed on a substrate. Ripples, microscopic corrugations of a graphene membrane, are considered inevitable to stabilize the graphene crystal in three-dimensional space, called intrinsic ripples,[4] and observed experimentally in a suspended graphene.[5] The graphene placed on a substrate, on the other hand, exhibits ripples basically following across the corrugations of the substrate underneath[6, 7, 8, 9, 10] except when it is placed on an ultra flat substrate.[9]

The ripples are discussed to affect the various electronic properties of graphene.[3, 11, 12] As for the transport properties, it has been shown experimentally rippling is the ultimate source of scattering when extrinsic disorder is eliminated.[13] Owing to ripples, on the other hand, when a magnetic field is applied parallel to the graphene plane (averaged two-dimensional plane), the magnetic field component normal to the local surface of ripples is created according to the gradient of the local surface against the magnetic field. Because ripples vary in size and in curvature from place to place, a random magnetic field with zero mean is produced in the graphene sheet (corrugating membrane).

Dirac fermions in graphene exhibit exotic electrical properties such as a novel quantum Hall effect, high carrier mobility, etc. Investigations of electrical transport properties of Dirac fermions in a random magnetic field coupling with ripples are attractive. In the present paper we report the experimental results of the magnetoresistance in a random magnetic field produced by applying a magnetic field parallel to the graphene plane.

2. Experimental details
The sample is a graphene flake produced by mechanical exfoliation from a HOPG crystal and deposited on a Si/SiO₂(306nm) wafer. The sample was annealed in H₂/Ar ambience (1.5 ℓ/min,
respectively) at a temperature of 200 °C for two hours before and after the electron beam lithography for contacts. The shape of the sample is trapezoidal and the parallel sides are the source and the drain contact, respectively. (See lower right inset of Fig.1) We use the averaged value of 2.4 µm as the sample width to calculate the resistivity from the resistance. The carrier density \( n \) was controlled applying a gate voltage \( V_g \) to \( n \)-type Si substrate(0.01Ω cm) and was calculated according to the equation 

\[
n = 7.1 \times 10^{10} (V_g - V_{CNP}) \text{cm}^{-2},
\]

where \( V_{CNP} \approx 11 \text{ V} \) is the gate voltage corresponding to the charge neutrality point (CNP). The coefficient was estimated from the thickness of the SiO\(_2\) layer. All the measurements have been done using a standard lock-in technique with 87 Hz and the sample current of 100 nA at temperature \( T \approx 80 \text{ mK} \).

Figure 1 shows the gate voltage dependence of the two-terminal resistance \( R_{SD} \). The upper left inset shows the gate voltage dependence of \( R_{SD} \) measured in a magnetic field of 15 T applied normal to the graphene plane. Quantized plateaus show the sample is a monolayer graphene. The plateau value of \( N = 0 \) for electrons shows higher values than expected. Because the present sample is a two terminal device, this is considered as a result of contact resistance. We consider this contact resistance does not change the results in the present experiment.

3. Results and discussions

Figure 2 shows the parallel magnetic field \( B_{||} \) dependence of the magnetoresistance \( \Delta R_{SD} = R_{SD}(B) - R_{SD}(0) \) at typical gate voltage in the hole region, around CNP, and in the electron region, respectively. The magnetic field \( B_{||} \) was applied along the source-drain direction to minimize the additional effect of the parallel magnetic field to the magnetoresistance.[14] The misalignment of the magnetic field from the graphene plane was estimated to be less than 0.04 degree. Although the parabolic dependence is observed in the overall behavior, negative magnetoresistance appears in low magnetic fields. This negative magnetoresistance comes from the weak localization effect due to normal component of the random magnetic field. In order to subtract the contribution of the weak localization to the resistance, we have measured magnetoresistance in low magnetic fields normal to the graphene plane at each gate voltages. We assume the negative magnetoresistance in parallel magnetic fields is governed by the rms value of the normal component of the random magnetic field: \( \overline{B_{\perp}} \). We have made try and error calculation so that the resultant resistance shows a parabolic dependence on \( B_{||} \) after the
Figure 2. Magnetoresistance $\Delta R_{SD} = R_{SD}(B_{||}) - R_{SD}(0)$ against parallel magnetic field $B_{||}$ at typical gate voltage $V_g$ (a) in the hole region, (b) around CNP and (c) in the electron region, respectively. Upper two traces are vertically displaced for clarity. The negative magnetoresistance due to the weak localization is observed in the low magnetic fields.

subtraction of the negative magnetoresistance. We found $B_{\perp} = 40$ mT for $B_{||} = 15$ T satisfies with the data of all gate voltages. Figure 3 shows an example how the correction has been done.

After the correction of the effect of weak localization, the magnetoresistance shows parabolic dependence against $B_{||}$. We have done the same correction on the data of all other gate voltages and calculated $\Delta \rho = \rho(B_{||}) - \rho(0)$. Figure 4 shows $\Delta \rho$ against $B_{||}^2$ for typical gate voltages for the hole region, around CNP, and the electron region, respectively. Although large fluctuations are observed in some data, we have done linear fit to all the data and obtained the coefficient $C$, where $\Delta \rho = CB_{||}^2$. Figure 5 shows the gate voltage dependence of the coefficient $C$. The value of $C$ has a maximum at CNP and decreases rapidly as the carrier density increases.

For the conventional two-dimensional electron system (2DES), the magnetoresistance $\Delta \rho$ in a weak random magnetic field with zero mean is predicted theoretically[15] as $\Delta \rho \propto B_{amp}^2 n_s^{-3/2}$ and confirmed experimentally,[14] where $B_{amp}$ is the amplitude of the random magnetic field and $n_s$ is the electron density. Recently, the magnetotransport measurements of graphene in parallel magnetic fields have been reported by Lundeberg and Folk.[16] They derived an equation for
Figure 4. Magnetoresistivity $\Delta \rho = \rho(B_{||}) - \rho(0)$ against $B_{||}^2$ obtained from the corrected magnetoresistance at gate voltage $V_g$ corresponding to Fig.2. Upper two traces in figure (c) are vertically displaced for clarity.

magnetoresistance due to random magnetic fields as,

$$\Delta \rho(n, B_{||}) = \alpha Z^2 |n|^{-3/2} B_{||}^2,$$

(1)

Figure 5. Gate voltage dependence of the coefficient $C$ which is obtained by linear fit to the data in Fig.4 as $\Delta \rho = C B_{||}^2$. The upper scale is the carrier density calculated assuming the charge neutrality point $V_{\text{CNP}} = 11V$. The solid lines show $|n|^{-3/2}$ dependence fitted in high carrier density region.

According to the equation (1), we get $C = \alpha Z^2/(Rrh|n|^{3/2})$. The solid lines in Fig.5 show $|n|^{-3/2}$ dependence for $\alpha Z^2/R = 1.9 \times 10^{-10}$ m. In the high hole density region, the coefficient $C$ shows $|n|^{-3/2}$ dependence. This is rather surprising result when we consider the difference in energy dispersion relation between the graphene and the conventional 2DES. In Ref. 16, they also observed $\Delta \rho \propto |n|^{-3/2}$ in the hole region of $1 \times 10^{16}$ m$^{-2} \leq |n| \leq 4 \times 10^{16}$ m$^{-2}$ at $B_{||} = 8$T.

Around CNP, on the other hand, the values of $C$ is apparently smaller than the value expected. It is reported that electron-hole paddles are formed at carrier density near CNP and the effective carrier density is higher than the value estimated using the capacitance.[17] The value of $C$, as
a result, will be smaller than the value expected. The carrier density region where \( C \) deviates from \( |n|^{-3/2} \) dependence shown in Fig.5 is approximately \( |n| < 1 \times 10^{16} \text{ m}^{-2} \). This value is an order of magnitude larger than the previous experiments.\cite{17} We consider this result represents the quality of the present sample shown by the broad peak of the gate voltage dependence in Fig.1.

Finally, we discuss on the value of \( \alpha \). We have done AFM measurements on two monolayer graphene exfoliated from the same HOPG flake using the same method as the sample in Fig.1. Using the \( Z(x, y) \) data, we calculated \( Z \), the rms value of the deviation of \( Z(x, y) \) from the mean value, and the correlation length \( R = (R_x + R_y)/2 \) calculating the correlation \( < Z(x, y)Z(x + \Delta x, y) > \) for \( R_x \) and \( < Z(x, y)Z(x, y + \Delta y) > \) for \( R_y \). We obtained \( Z = 0.236 \text{ nm}/0.232 \text{ nm} \) and \( R = 14 \text{ nm}/25 \text{ nm} \) for the two samples, respectively. The values of \( Z \) agree with each other and correspond to that of the bare SiO\(_2\)\cite{10}. The variation of \( R \) suggests that the corrugation of SiO\(_2\) is not homogeneous and it is reflected in the graphene ripples on top.\cite{8, 9} When we use the values of \( Z \) and \( R \) shown above, we get \( \alpha = 48 \) and \( 88 \) for the two samples, respectively. In Ref.16, they estimated \( Z \) and \( R \) combining measurements of the magnetoresistance and the daphasing time of the weak localization. They observed \( \Delta \rho \) against \( B_{||}^2 \) but without the correction of weak localization. In addition, the magnetic field \( B_{||} \) is not parallel to the direction of the sample current. The coefficient \( C \) in their calculation, hence, is presumably smaller than the correct one and they obtain \( \alpha \approx 2.8 \). In the present experiment, on the other hand, the relation between the ripples and the magnitude of the magnetoresistance in a parallel magnetic field, more experimental and theoretical studies are inevitable.

4. Summary
We have measured the magnetoresistance of a graphene in a random magnetic field created by applying a magnetic field parallel to the graphene sheet with ripples. The magnetoresistance has exhibited the same magnetic field dependence, \( \propto B_{||}^2 \), and, contrary to our expectation, the same carrier density dependence, \( \propto n^{-3/2} \), as the conventional 2DES in random magnetic fields.

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