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The investigation of transport properties of mesoscopic graphite in high magnetic field

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Abstract

The electrical transport properties of mesoscopic graphite have been investigated in a gate voltage configuration. Few layer graphene structures made from Kish graphite exhibit Shubnikov-de Haas (SdH) oscillations in magnetic fields up to 33 T, with a strong gate voltage dependence. A two band model can be used to explain the linear dependence of the SdH frequency on the gate voltage. The temperature dependence of the SdH oscillation amplitude allows the determination of the effective masses of the carriers, which remain comparable between mesoscopic and bulk graphite samples. However, mesoscopic graphite thinner than 130 nm does not exhibit the field induced charge density wave transition seen in bulk samples above 25 T at low temperatures.

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1. Introduction

Graphene is the basic unit of graphite. It consists of a single layer of carbon atoms densely packed into a benzene-ring structure. The discovery of carbon nanotubes, which are equivalent to graphene sheets rolled into nanometer sized cylinders, has renewed the interest in graphite materials [1]. The peculiar band structure of graphene [2] produces remarkable electronic properties in carbon nanotubes (e.g. it can be considered as a prototype of a one-dimensional quantum wire). Very thin layered graphite samples which range in thickness from 1 nm to 100 nm have been synthesized by different methods (e.g. either chemical [3] or mechanical extraction [4–6], or direct synthesis on substrates [7,8]). Electrical transport measurements in graphitic disks with a thickness of ~40 nm exhibit a suppression of magnetoresistance up to 10 T [9]. A coulomb blockade phenomena has been demonstrated in low-temperature transport measurements on gated, quasi-2D graphite quantum dots [10].

Recent experiments few layer graphene (FLG – thickness between 10 nm and 100 nm) have shown that there is a strong modulation of the magneto-resistance and the Hall signal as a function of gate voltage [6,11] which has never been observed in bulk graphite [12]. Moreover, the type of carriers in few layer graphene can be adjusted by changing the gate voltage (e.g., electrons (holes) are the majority carriers when positive (negative) gate voltage is applied). Recently, an unusual quantum hall effect has been discovered (the quantization condition is described by half integer values rather than integer values) in graphene [13–15]. The half-integer phase shift observed in magneto-oscillation experiments is due to the topology of the graphene band structure which has a linear dispersion relation and zero rest mass [16].

It has been long known that a field induced charge density wave (CDW) transition appears in bulk graphite at high magnetic fields of order 25 T or more [17–19]. However, this phenomenon in few layer graphene has not, to

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our knowledge, been investigated before. Hence, the purpose of this work is to explore the magnetoresistance of this material (thickness of 15 nm and 130 nm) in high magnetic field (up to 33 T), and to examine the field induced charge density wave transition.

2. Experimental method

Bulk Kish graphite samples were cleaved in a conventional manner with adhesive tape and transferred onto a SiO_2/n-doped Si substrate by pressing mechanically by hand. In this manner, samples with a lateral size of ~20 μm and thickness between 10 nm and 200 nm can be obtained. Once the samples are on the substrate, Cr/Au electrodes with the thickness of 5/25 nm are fabricated onto the sample by photolithography and thin film evaporation. Fig. 1 shows the image of a typical sample taken by both optical and atomic force (AFM) microscopy. In addition, the doped silicon substrate is used as a gate electrode with 360 nm of SiO_2 acting as the gate dielectric. The resistivity measurements were done by using a conventional four-probe method with a constant AC current of 0.1 μA and frequency 17 Hz. In addition, a positive or negative gate voltage is applied to the doped Si substrate, and the ground for the gate potential is referenced to the ground potential of the 4-terminal current source.

3. Results and discussion

Fig. 2 shows the Shubnikov-de Haas (SdH) oscillations in 15 nm thick sample at 1.4 K for different gate voltages. The SdH oscillations at zero gate voltage are observed up to 33 T. This observation differs from that seen in bulk samples, where the SdH oscillations are in the quantum limit above ~10 T [19]. The effect of electric field changes the frequency of the SdH oscillations. The frequency of the SdH oscillations, B_F is related to cross-sectional area of the Fermi surface, S and can be expressed as $B_F = Sh/4\pi^2 e = k_f^2 h/4\pi e$, where h, k_f, and e are Planck's constant, the Fermi momentum wave vector and the electron charge, respectively. Assuming the energy dispersion relation of the carriers is $E_k = \hbar^2 k^2/2m$, then $B_F = mE_F/e\hbar$. In a two-dimensional system, the charge carrier concentration, n can be expressed as $n = 2mE_F/\pi\hbar^2$. We further assume that there is induced charge $n_{ind} = C_{gate}V_{gate}/e$, when the gate voltage, V_{gate} is applied. Here, C_{gate} is the capacitance per unit area of the gate (SiO_2). By using a reference $E_F = 0$ when $V_{gate} = 0$, then the SdH frequency can be related to V_{gate} as

$$B_F = \frac{hC_{gate}}{4e^2}|V_{gate}| \quad (1)$$

The linear dependence of the frequency of the SdH oscillations on gate voltage is consistent with our data, as shown in Fig. 3. Here, we estimate C_{gate}, using Eq. (1) to be (49.7 ± 4.4) aF/μm^2. Based on geometry considerations, the value of C_{gate} (360 nm SiO_2) is 104 aF/μm^2. The difference in these values most likely due to a partial screening

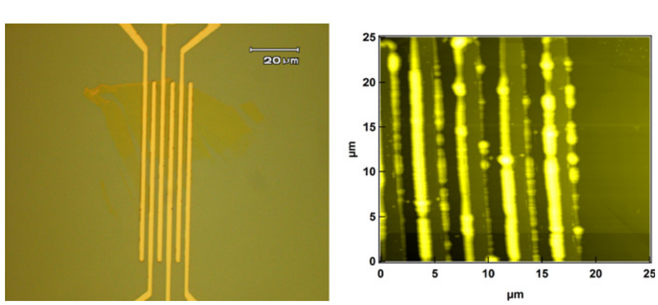

Fig. 1. Left: Optical microscope image of the FLG. The gaps between the leads is 2 μm. Right: AFM image of the FLG. The thickness of this sample is ~15 nm.

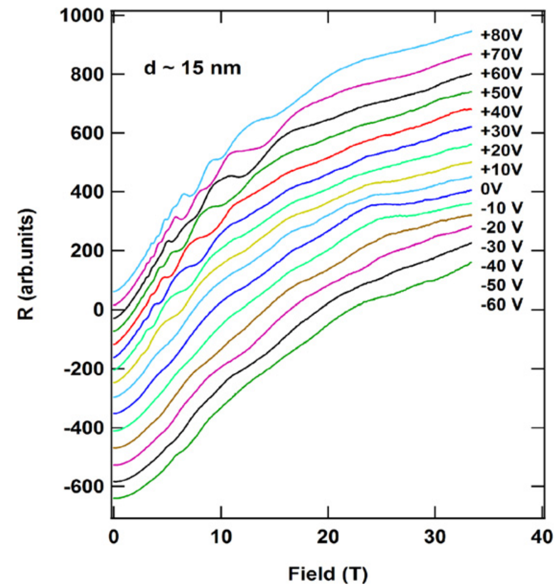

Fig. 2. The resistivity of a 15 nm graphite sample as a function of magnetic field at 1.4 K for different gate voltages.

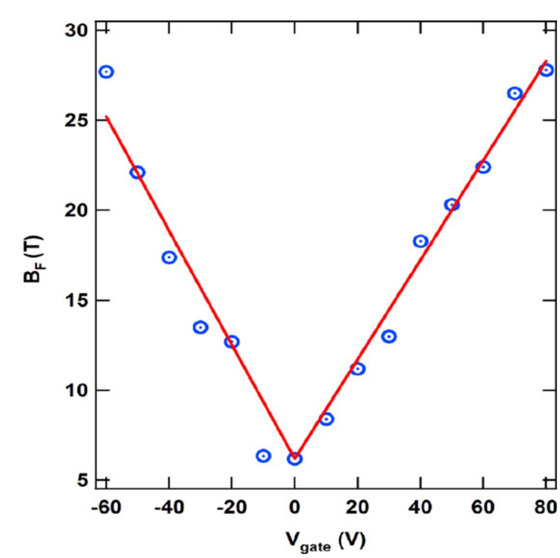

Fig. 3. Frequency of the SdH oscillations obtained from Fig. 2 as a function of gate voltage.