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Hole dephasing caused by hole–hole interaction in a multilayered black phosphorus

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Abstract

We study the magnetotransport of holes in a multilayered black phosphorus in a temperature range of 1.9 to 21.5 K. We observed a negative magnetoresistance at magnetic fields up to 1.5 T. This negative magetoresistance was analyzed by weak localization theory in diffusive regime. At the lowest temperature and the highest carrier density we found a phase coherence length of 48 nm. The linear temperature dependence of the dephasing rate shows that the hole–hole scattering processes with small energy transfer are the dominant contribution in breaking the carrier phase coherence.

Keywords: black phosphorus, weak localization, hole dephasing

(Some figures may appear in colour only in the online journal)

Layered two dimensional materials have attracted great interests in the scientific community lately [1]. Added to the family of graphene and transition metal dichalchogenides, the more recently studied material black phosphorus has its own merits. It has a band gap changing from 0.3 eV to 2 eV when it is thinned from bulk to a monolayer [2, 3]. Superior to graphene and transition metal dichalchogenides, it is blessed with high mobility and high current on/off ratio. With boron nitride encapsulation, quantum Hall effect was observed in multilayer black phosphorus [4, 5]. In this work, we study magnetotransport in a multilayer at low temperatures. We observed negative meganetoresistance and analyzed with weak localization (WL) theory. We found that the temperature dependence of the carrier dephasing rate exhibits that the hole–hole interaction is the dominant contribution to the dephasing mechanism. Although in pervious literatures WL effect in black phosphorus has been reported [6–8], the seemingly linear temperature dependence of the dephasing rate was confined in a limited temperature range in the high temperature end of their experiments. In a previous report [6], the deviation starts at a quite high temperature of 5 K. In our results, linear dependence spans in the whole temperature range from 2 K to 22 K in high carrier densities, and deviation from linear relation exists in the lowest carrier density.

The device was made with an exfoliated black phosphorus multilayer on SiO_2/Si substrate, where the highly doped Si was used as a back gate. The electrodes were defined by e-beam lithography followed by metal deposition. Measurements were performed in a variable temperature cryostat with four-terminal low-frequency lock-in technique. Figure 1 inset shows the optical image of the device. From the optical contrast, we estimate the layer is about 10 nm thick. It does not affect the discussion of the WL or hole–hole interactions in the channel without knowing the exact value of the layer thickness since for exfoliated black phosphorus field effect transistors the carriers are confined in a thickness of 2–3 nm on the surface [5, 9]. This thickness is much shorter than the phase coherence length that lies in range of 20–48 nm, and the thermal length $l_T = \sqrt{\frac{\hbar D}{k_B T}}$ that lies in range 9.1–42 nm in the

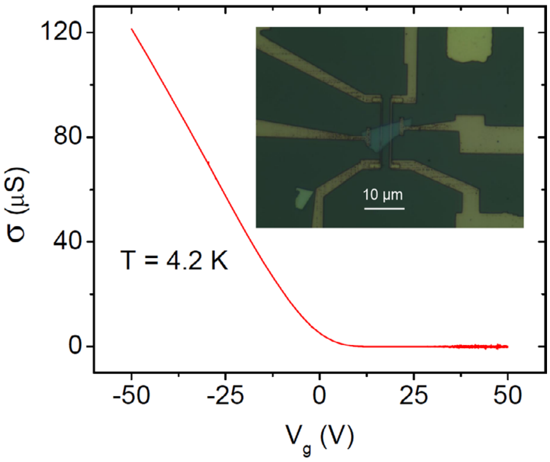

Figure 1. Gate dependence of conductivity measured at 4 K in zero magnetic field. Inset shows the optical image of the device.

studied temperatures. Here $\hbar$ is the reduced Planck constant, k_B is the Boltzmann constant and D is the diffusion constant.

The measured gate effect conductivity was shown in figure 1. From the measurement at 4 K, the field effect mobility μ was estimated to be 2.2×10^2 cm^2 Vs^{-1}, and the corresponding momentum relaxation time τ is 3.22×10^{-14} s, here we used the hole effective mass 0.26 m_0 [10], with m_0 the free electron mass. In the experimental temperature range of this study, the field effect mobility is not supposed to change with temperature [5, 11]. The Drude conductivity σ_0 was estimated from $\sigma = \sigma_0 + \frac{Ce^2}{\pi^2\hbar}\ln(\frac{T}{T_0})$, here C is a constant and T_0 is a characteristic temperature [12] that depends on the carrier transport property of the conducting channel. The temperature dependence of the zero field conductivity and the linear fit of the data were presented in figure 2. With decreasing carrier density, the slope of the curves decreases slightly. From the Drude conductivity the diffusion constant D and the transport field $B_{\mathrm{tr}} = \hbar/4De\tau$ were obtained at various carrier densities. Values of parameter $k_F l$ were calculated from $\sigma_0 = \frac{2e^2}{h}k_F l$, where k_F is the Fermi wave vector and l is the mean free path. Concerning the valley degeneracy in black phosphorus, theoretical calculations for a three dimensional case show that there is a single valley in the valance band at Z point [13]. In the analysis of the WL of multilayered black phosphorus, the valley degeneracy factor $g_v = 2$ was used in [6]. In [4] the magnetotransport data does not show a clear sign if there exists a valley degeneracy and result in [5] reveals a single valley effect at high fields 10–35 T. Since our measurement is at low fields up to 1.5 T, we applied $g_v = 2$ in the analysis of this work. Some of the transport parameters of the device we studied are presented in table 1.

It should be noted that the WL theory is derived on the condition $k_F l \gg 1$. We see from Table I that the values of $k_F l$ in the studied device do not satisfy this condition. This means that the WL theory is not expected to be well applied. In this scenario there had been arguments that in practice the WL formula with a reduction prefactor can be used to fit the magneto conductance to extract the dephasing rate [14–16].

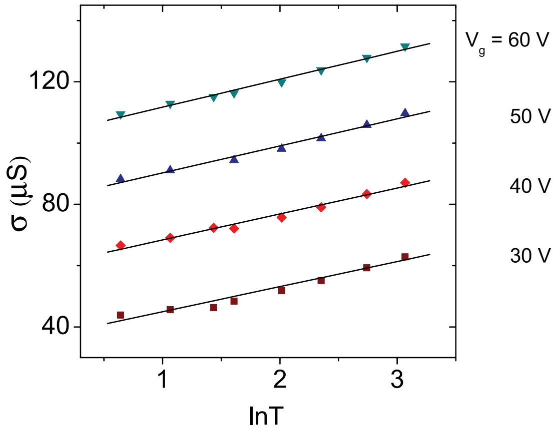

Figure 2. Zero field conductivity as a function of temperature. Symbols are experimental results; from the linear fit (the lines) the Drude conductivity σ_0 at various gate biases was calculated.

Table 1. Parameters of the device at various carrier density.

n (10^{12} cm^{-2})	D (cm^2 s^{-1})	$k_F l$	B_{tr} (T)
2.34	2.34	1.05	21.7
3.04	3.05	1.37	16.7
3.71	3.73	1.56	13.7
4.36	4.38	1.96	11.7

The WL correction to conductivity can be expressed with the equation [14, 17, 18]

$$\delta\sigma = \alpha\frac{2e^2}{\pi h(1+\gamma)^2}[\psi(\frac{1}{2}+\frac{\gamma}{b}) - \psi(\frac{1}{2}+\frac{1}{b}) - \ln\gamma], \quad (1)$$

where $\psi(x)$ is the digamma function, $\gamma = \tau/\tau_\varphi$, τ_φ is the phase decoherence time, and $b = \frac{1}{1+\gamma^2}\frac{B}{B_{\mathrm{tr}}}$. α is the reduction prefactor discussed above. For non-interacting particles α is temperature independent. In a multivalley semiconductor, α can vary depending on the strength of the intervalley scattering, where strong intervalley scattering tends to further reduce the value of α.

Figure 3 shows the fitting results at two carrier densities $n = 4.36 \times 10^{12}$ cm^{-2} and $n = 3.04 \times 10^{12}$ cm^{-2}. We found that the experimental data can be fitted well in the field range $B < 0.7$ T. In larger filed there is the deviation from equation (1), since this expression may have overestimated the suppression of the quantum interference effect in lager magnetic field, thus it gives the magnetoresistance with a larger value [19]. In the three higher carrier densities ($n = 3.04, 3.71, 4.36 \times 10^{12}$ cm^{-2}) the reduction factor $\alpha = 0.34$ whilst for the lowest density ($n = 2.34 \times 10^{12}$ cm^{-2}) this value is significantly smaller, $\alpha = 0.23$. Our results confirmed that for a specific carrier density α does not depend on temperature, which is in agreement with previous experiments [16, 20]. The fitted value γ varies from 0.0060 to 0.098, corresponding to a phase coherence length 10 to 100 times larger than the mean free path. In a two dimensional conductor at low temperatures, when the contribution from the phonon scattering to the dephasing mechanism can be neglected [21, 23], the hole–hole scattering processes are in dominance in the dephasing mechanism. This hole–hole interaction contributed

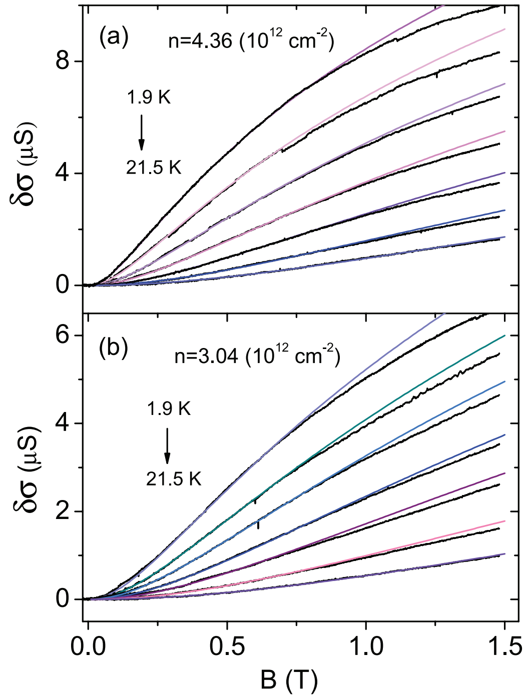

Figure 3. WL correction of conductivity as a function of magnetic field. Black lines represent experimental results at $T = 1.9$, 2.9, 5.0, 7.5, 10.5, 15.5, 21.5 K. Coloured curves are calculated values to fit to equation (1). (a) $n = 4.36 \times 10^{12}$ cm^{-2}. (b) $n = 3.04 \times 10^{12}$ cm^{-2}.

temperature dependence of the dephasing rate can be linear at $k_B T\tau/\hbar \ll 1$, or quadratic at $k_B T\tau/\hbar \gg 1$. The quadratic temperature dependence originates from the scattering with large momentum transfers in a disorder free conductor whilst the linear temperature dependence is due to processes with small energy transfers in a disordered conductor. The value of $k_B T\tau/\hbar$ in this device varies from 0.008 to 0.09 in the experimental temperature range. We calculated the theoretical prediction of τ_φ^{-1} in diffusive regime($k_B T\tau/\hbar \ll 1$) from [22, 23]

$$\tau_\varphi^{-1}(T) = \frac{k_B T}{2E_F\tau}\ln\left(\frac{2E_F\tau}{\hbar}\right). \qquad (2)$$

Here $E_F = \pi\hbar^2 n/m^*$ is the Fermi energy, m^* is the effective mass of the carriers. We can see from figure 4(a) that in the measured temperature range, at the two higher carrier densities the τ_φ^{-1} obtained from WL measurement agree reasonably well with the theoretical value by equation (2) except with an offset shift, while at the lowest carrier density ($n = 2.34 \times 10^{12}$ cm^{-2}) there is a large deviation. We can also see that the slope of the theoretical lines decreases with decreasing carrier density, but in experiments, only slight changes of slope are observed. In the case that the zero field conductivity $\sigma \sim e^2/h$ (which is the case in our lowest carrier density), the standard weak localization theory is inadequate [14], the conducting system is in weakly insulating regime. The curves can still be fit by the weak localization theory, but the extracted dephasing time may not reflect the real nature of the dephasing mechanism. In this study we present this analysis and leave this for open discussions. In figure 4(b) the temperature dependence of dephasing length $l_\varphi = (D\tau_\varphi)^{1/2}$ was presented. At the highest carrier density, l_φ decreases from 48 nm to 19 nm as the temperature changes from 1.9 K to 21.5 K.

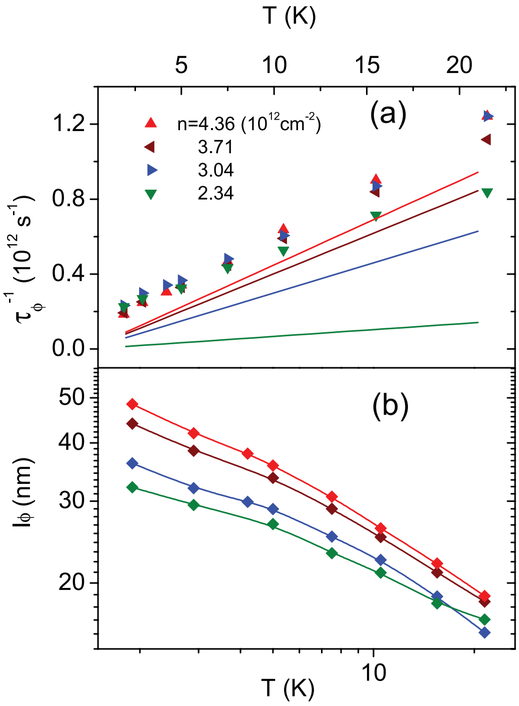

Figure 4. (a) Temperature dependence of the carrier dephasing rate. Symbols are results from experimental analysis. Lines are calculation with equation (2). We can see that at high carrier density the experimental results conform reasonably well with theoretical prediction, while at low densities there is large deviation. (b) Phase coherence length as a function of temperature.

We compare our results with previous reports on multilayer black phosphorus in WL study performed with bare thin layer [6, 8] or boron nitride encapsulated layers [7]. The devices in these reports have comparable or somewhat higher mobilities compared with our device ($\mu = 2.2 \times 10^2$ cm^2 Vs^{-1}) at similar carrier densities. The order of the observed dephasing lengths in these reports are also comparable with this study. For boron nitride encapsulated black phosphorus layer [7], the mobility is higher, the Drude conductivity is higher, thus the dephasing length could be twice longer than in our experiment. The temperature dependence of the dephasing rate is linear in [6, 7] and in [8] it follows a $T^{-2/3}$ dependence. The $T^{-2/3}$ dependence was explained by the anisotropic effect of the puckered structure of black phosphorus that contributes to a quasi one dimensional conducting channel. All these studies observed a saturation of the phase coherence time at a temperatures of 1 K, 2 K and 5 K. Saturation of dephasing time at very low temperatures were observed in various conductors and explained by various mechanism [24, 25]. We have not observed a saturation of the dephasing time until the lowest measured temperature of 2 K. It is hard to predict whether there is a saturation of the dephasing time in this device at lower temperatures. We will not go into further discussion of this issue and leave it for future investigations.

In this work, we studied magnetoresistance in a multilayered black phosphorus and compared the results with earlier works. The hole dephasing rate shows a linear temperature dependence demonstrating that hole–hole interaction is the dominant process in the dephasing mechanism. We found that a reduction prefactor was needed to get a good fit with the WL theory. This reduction factor does not depend on temperature and stays the same in the three high carrier densities but decreases further in the lowest carrier density. Our results are in agreement with the localization theory in a disordered conductor.

Acknowledgments

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