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Weak Localization in Graphene: Experiments and the Localization Length

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Abstract. We compare the density dependence of the weak localization peak of graphene samples with the one of the computed localization length. The samples show a uniform density dependence of the relative magneto-resistance, which is similar to the computed relative localization length dependence. This analysis is performed for high mobility samples, such as large single crystal flakes as well as low mobility devices and polycrystalline large scale graphene. The magnetic field dependence of the relative localization length exhibits a striking universal behavior.

Keywords: Graphene, Weak localization, Disorder
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Weak localization (WL) is very different in graphene, compared to other materials, because of the existence of two degenerate Dirac valleys. If inter-valley scattering is suppressed, no WL exists. Hence, the strength of WL is strongly dependent on the strength of inter-valley scattering. Theoretical works have examined this dependence and general expressions for the WL correction in graphene were obtained for various scattering parameters [1, 2]. However, when fitting experimental data using these expressions, they often lead to very different results depending on the fitting assumptions [3].

To further clarify the physics of WL in graphene, we performed experiments on large scale graphene as well as lithographically defined Hall bars and graphene nano-ribbons, in addition to large (over 100 µm) single crystal grains, of which some show strong dendritic structures, dubbed graphlocons. Monolayers of graphene were grown by chemical vapor deposition (CVD) of hydrocarbons on 25 µm-thick commercial Cu foils. The CVD process used was similar to those described in previous works [4, 5, 6]. Graphene’s experimental properties are reviewed in Cooper et al. [7].

The overall experimental behavior can be summarized as follows: at low temperatures, higher mobility samples, typically above 500 cm²/V·s show a narrow peak in the resistance at zero field (as shown in figure 1). With decreasing mobility, the peak exhibits a strengthening and broadening, which can extend to several Teslas. These low mobility samples show a very wide negative magnetoresistance even at very low temperatures (below 1K). All samples we measured show a weak localization peak at zero field. The relative change in resistance is typically of the order of 0.5 to 5% in higher mobility samples and below 1K, while it can be substantially higher for low mobility samples. This is not very surprising, since McCann’s expression yields \( \Delta \rho / \rho \sim \rho \Delta F(B) \), where \( \Delta F(B) \) describes the magnetic field dependence and \( \rho \) is the resistivity [2].

We looked, in particular, at the density dependence of the weak localization peak for a high mobility sample (\( \sim 5000 \) cm²/Vs), which shows a field effect on/off ratio of 10 and exhibits the quantum Hall effect at 8T. The results are shown in figure 2. Interestingly, the relative change in resistance of the weak localization peak does not depend much on the density.

We compared these experimental results with numerical simulations, using non-equilibrium Green’s functions to compute the resistance and the localization length (\( L_c \)) of disordered graphene flakes. \( L_c \) was extracted from the exponential increase with length of the flake’s resistance. The resistance and \( L_c \) show respectively, an overall in-
crease in the relative resistance and relative $L_c^{-1}$ at zero $B$, which does not depend significantly on the density (Fermi level).

In fact, the relative $L_c$ shows a nearly universal behavior as a function of magnetic field, i.e.,

$$\frac{L_c(B) - L_c(0)}{L_c(B)} \simeq 0.45 \left(1 - 1/\sqrt{1 + B^2/B_c^2}\right), \quad (1)$$

where $B_c$ scales with the width of the flake and the level of disorder.

Interestingly, not only does $L_c^{-1}$ show a weak localization behavior, but more importantly, this behavior can be used to analyze samples with much higher disorder, where McCann’s theory [2] breaks down. Indeed, we find that for low mobility samples, McCann’s theory does not fit the data, in contrast to using the $L_c$ dependence, which also fits the data that shows a very large broadening at $B=0$ at high disorder.

Summarizing, we studied the density dependence of the weak localization peak using different samples, including large single crystal dendritic flakes, where McCann’s theory of weak localization (McWL) is consistent with the data for high and intermediate mobilities and away from the Dirac point. With increasing disorder, the magnitude of the weak localization peak increases and broadens and can no longer be fitted with McWL. We propose here an alternate description based on the weak localization of the inverse localization length, which shows a universal behavior and recovers McWL at low disorder but changes at high disorder in agreement with experiments on low mobility graphene.

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