

Magnetic Commensurability Effect in Ballistic Graphene

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1. Introduction

The unique linear energy spectrum in graphene has led to the observation of intriguing ballistic transport phenomena, such as Klein tunneling [1]. In ballistic graphene devices, scattering of charge carriers by sample boundaries, namely boundary scattering, is a key element for understanding their transport properties, because the charge carrier scattering probability at sample boundaries becomes significantly larger than in the bulk region.

In the mesoscopic wire system made from conventional semiconductor-based two-dimensional electron system, it has been established that, if the charge carriers travel ballistically in the bulk region and are scattered diffusively at the sample boundary, the device exhibits anomalous magnetoresistance peaks owing to the magnetic commensurability effect between cyclotron radius R_c and wire width W . Moreover, by studying anomalous magnetoresistance peak structures, the probability for specular scattering, namely specular parameter p , can be extracted.

In this work, we report on the observation of anomalous magnetoresistance peaks due to diffusive boundary scattering in ballistic graphene wire device. Magnetoresistance amplitude analysis suggests nearly zero probability of specular scattering at graphene boundaries. Moreover, the magnetoresistance peak field scales with the ratio of cyclotron radius R_c and wire width W as $R_c/W = 0.9 \pm 0.1$, which differs from that of a classical semiconductor 2D electron system where $R_c/W \sim 0.55$.

2. Experimental

The graphene/hexagonal boron nitride (GBN) mesoscopic wire system was fabricated using the mechanical transfer technique of monolayer graphene on arbitrary substrates [2]. First, relatively thick h-BN crystals (~ 10 nm) were deposited on a Si wafer using a mechanical exfoliation technique. A monolayer graphene was deposited on a spin-coated polymethylmethacrylate (PMMA) layer and transferred on a h-BN crystal using an alignment technique under an optical microscope. Monolayer thickness of graphene layer was verified by Raman spectroscopy and

atomic force microscopy measurements. Finally, wire-shaped geometry was defined using the standard electron-beam lithography and subsequent oxygen plasma etching technique. Metal contacts were defined by electron-beam lithography followed by evaporation of Pd (80 nm) and lift-off technique. The resist residues were removed by annealing in Ar/H₂ (97:3) gas flow for 6 h.

Transport measurements were carried out employing the standard lock-in technique with a small alternating current of $I_{ac} = 100$ nA in a variable temperature insert. A conducting Si substrate was used as a global back gate to tune charge carrier density as $n = C_g(V_g - V_{Dirac})$ where $C_g = 1.07 \times 10^{-4}$ F/m² is the gate-capacitance and V_{Dirac} is the value of V_g at charge neutrality point. The fabricated device exhibited high mobility $\mu \sim 70,000$ cm²/Vs at $T = 4$ K, and the elastic mean free path reached ~ 1 μ m at high charge carrier density $n \sim 3 \times 10^{12}$ cm⁻².

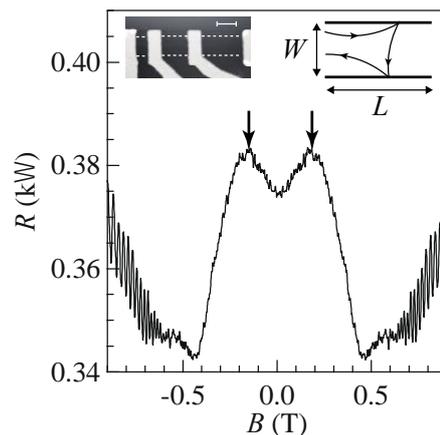


FIG. 1: Anomalous magnetoresistance peak structures measured at $T = 4$ K for channel length $L = 2.3$ μ m and width $W = 1.0$ μ m device with gate-bias voltage $V_g = -45.0$ V. The inset shows the atomic force microscopy image of the sample studied in this work.

3. Results and Discussions

Figure 1 shows magnetoresistance curves measured at $V_g = -45$ V. As magnetic field B was increased, resistance R increased and took maximum at $B_{\max} = \pm 0.21$ T. As B was further increased, R decreased with B and showed minimum at $B_{\min} = \pm 0.51$ T. For larger B , R oscillated as a function of B , which can be attributed to Shubnikov-de Haas oscillation.

To study the origin of magnetoresistance peaks, we measured anomalous magnetoresistance curves by changing charge carrier density n by gate-bias voltage V_g . As we decrease n , the peak positions B_{\max} were decreased. The value of B_{\max} scaled with the ratio of cyclotron radius R_c and sample width W as $R_c/W = 0.9 \pm 0.1$. This observation indicates the magnetic commensurability effect between R_c and W . Therefore the observed anomalous magnetoresistance curves can be attributed to diffusive scattering of charge carriers at sample boundary in graphene mesoscopic wire system. Note that this is the first observation of anomalous magnetoresistance curves in graphene.

The proportionality constant between W and R_c differed from the case of conventional semiconductor two-dimensional electron system where $W/R_c \sim 0.55$ [1]. This observation suggests that the standard relation between R_c and W in semiconductor two-dimensional electron systems has to be modified to explain the observed transport phenomena in graphene.

4. Conclusion

We studied magnetotransport properties of ballistic graphene wires fabricated on graphene/hexagonal boron nitride heterostructure. The magnetoresistance curves exhibit characteristic peak structures owing to the magnetic commensurability effect between cyclotron radius and sample width. The analysis suggests that the values of R_c and W scale as $R_c/W = 0.9 \pm 0.1$. This is in contrast to the semiconductor two-dimensional electron system where $R_c/W = 0.55$. The analysis also suggests nearly zero probability for specular scattering at the sample boundary.

These findings are fundamental step forward in understanding the effects of boundary scattering on the transport properties of nanostructured graphene devices such as graphene nanoribbons and graphene single electron transistors.

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