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Magnetoresistance oscillations in graphene antidot arrays

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Epitaxial graphene films have been formed on the C-face of semi-insulating 4H-SiC substrates by a high temperature sublimation process. Nanoscale square antidot arrays have been fabricated on these graphene films. At low temperatures, magnetoresistance in these films exhibits pronounced Aharonov–Bohm oscillations with the period corresponding to magnetic flux quanta added to the area of a single antidot. At low fields, weak localization is observed and its visibility is enhanced by intervalley scattering on antidot edges. At high fields, we observe two distinctive minima in magnetoresistance, which can be attributed to commensurability oscillations between classical cyclotron orbits and antidot array. All mesoscopic features, surviving up to 70 K, reveal the unique electronic properties of graphene. © 2008 American Institute of Physics. [DOI: 10.1063/1.2988725]
lalion $2R_c=2\sqrt{\pi N_s(h/eB)=a}$, carrier density $N_s$ is determined to be $\sim 7.5 \times 10^{12}/\text{cm}^2$, where $R_c$ is the cyclotron radius, $h$ is the Planck constant, and $a$ is the period of antidot arrays. The elastic mean free path $l_e$ is estimated to be $\sim 220 \text{ nm}$ in a reference sample without antidots. The elastic mean free path $l_e=2D/v_F$, where carrier diffusive constant $D=e^2/2\pi^2 \rho$, Fermi energy $E_F=hv_F\sqrt{\pi N_s}$, and $\rho$ is zero-field resistivity of graphene films. The $l_e$ is larger than the circumference of a single antidot ($\sim 125 \text{ nm}$) but a little bit smaller than the circumference of the central pinned orbits ($\sim 250 \text{ nm}$). It is not a fully ballistic transport from this estimation. The reason for the observation of the second magnetoconductance minima, corresponding to the pinned orbits around four antidots and requiring a much larger $l_e$, is not very clear at this moment. The third feature is the tiny structures superimposed on the measured trace, for example, between $\pm 2$ and $\pm 7 \text{ T}$. Universal conductance fluctuations are suppressed since the sample size ($\sim 2 \mu\text{m}$) is much larger than the phase coherence length. However, quantum interference effect is still observable because the antidot size ($\sim 40 \text{ nm}$) is smaller than the phase coherence length. These tiny periodic features are identified as AB oscillations, which are related to each magnetic quantum flux penetrating in one antidot cell. AB oscillations on an exfoliated graphene film have been demonstrated experimentally on a single lithographically defined ring. The conductance fluctuations with the origin of quantum interference effect have also been observed in narrow channeled epitaxial graphene films.

The black thick curve in Fig. 2(a) shows the measured magnetoconductance between $+2$ and $+12 \text{ T}$ with superimposed oscillatory features. By taking the difference of the measured curve and the black baseline curve obtained from smoothing the measured one, a pronounced AB periodically oscillatory curve is exhibited as shown as the gray curve in Fig. 2(a). The AB oscillation period $\Delta B=0.5 \text{ T}$ in this field range is consistent with the condition that the magnetic flux enclosed within the unit cell of the square antidot lattice changes by a single magnetic flux quantum, i.e., $\Delta B=(h/e)/a^2$ with $a=80 \text{ nm}$. The rms amplitude of AB oscillations is $\sim 0.01e^2/h$. For detailed discussions, Fig. 2(b) illustrates Fourier power spectrum of Fig. 2(a) with a broad peak centered around 0.47 T, with 0.57 and 0.40 T as the edges of the half-height width. It corresponds to the inner radius, middle radius, and outer radius of 48, 53, and 57 nm, respectively, if $\Delta B=(h/e)/(\pi r^2)$ where $\pi r^2$ is associated with the effective antidot area. It is consistent with the designed ge-

![FIG. 1.](image1) (Color online) (a) The sample layout with a $2 \times 2 \mu\text{m}^2$ graphene area and two-terminal metal contacts. (b) Electron microscopic image of antidot arrays with $\sim 40 \text{ nm}$ holes and $\sim 80 \text{ nm}$ pitches. The commensurate orbits around one antidot and four antidots are sketched to illustrate the physical origin of Weiss oscillations. (c) Magnetoconductance of the graphene antidot arrays measured at $T=470 \text{ mK}$. On top of the commensurability oscillations, periodic features are clearly visible as also highlighted in Fig. 2(a).

![FIG. 2.](image2) (a) The solid curve is the measured magnetoconductance. The thin curve is the “baseline” after smoothing the original measured curve. The periodically oscillatory curve is the subtraction of the two black curves. The vertical straight lines are guide to the eyes showing periodic $B$ feature of observed AB oscillations. (b) Fourier spectrum of the oscillatory gray curve between 2 and 12 T. The solid curve is after six point smoothing. The two vertical straight lines with arrows indicate the positions for half-height of the observed $h/e$ peak, as used for the calculation of the inner and outer radii of the “AB-ring” structure around one antidot.

ometry well with 40 nm holes and 80 nm pitches. The relatively large inner radius could be related to overdeveloped resist patterns, plasma overetching, and certain depletion length of graphene edges with unpassivated dangling bonds. The magnetic length \( l_B = \sqrt{\hbar/\epsilon B} = 9.2 \text{ nm at } B = 6 \text{ T} \) or similar edge channels in the quantum Hall regime could also affect the data. The observed AB oscillations demonstrate that the epitaxial graphene on SiC is of high quality and at least has the quantum coherent length larger than 80–100 nm. The weak peak features around \( 1/B = 4 \text{ (1/T)} \) could be related to \( h/2e \) oscillations.\(^3,11\)

While universal conductance fluctuations are generally observed in small graphene flakes, weak localization correction is strongly reduced compared to the conventional 2D systems due to suppressed backscattering in graphene loosely coupled to the substrate.\(^12\)\(^14\) Short range scattering in epitaxial graphene due to tight binding to the substrate, short range scattering on the edges of antidots, and warping of the Fermi surface at high densities introduces intervalley scattering,\(^15\) which restores weak localization corrections.\(^16\) We observe pronounced negative magnetoresistance at low fields with a sharp cusp at zero field characteristic of weak localization in two dimensions, see Fig. 3(a). Moreover, at higher fields, magnetoresistance changes sign, which is expected for the case of strong intervalley scattering.\(^17\) We used the theory developed in Ref. 17 to analyze the data and extract both phase coherence length \( L_\phi \) and intervelley scattering length \( L_v \), see Fig. 3(b). \( L_v \) is found to be temperature independent and is approximately equal to the distance between antidots, suggesting that scattering on the antidot edges is the dominant intervelley scattering mechanism in our samples. \( L_\phi \) decreases with the increasing temperature, although it does not follow the 1/T dependence found in an unpatterned graphene.\(^15\) We also note that the range of field where weak localization is observed in an antidot array is much larger than that for the unpatterned samples. The temperature dependence of AB oscillations is also plotted in Fig. 3(c), which is consistent with the conclusion from Fig. 3(b) by weak localization peak fitting.

In conclusion, we present magnetotransport experiments on antidot arrays fabricated on epitaxially grown graphene films on SiC. The experiment demonstrates the observation of commensurability oscillations and AB oscillations arising from the artificially imposed lateral potential modulation. The intervelley scattering length and the phase coherence length in graphene antidot arrays are also investigated to explain the temperature dependence of the weak localization and the weak antilocalization.

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