Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp326-327

PS-9-14L

Transport Spectroscopy of Field-induced Quantum Confinement in Graphene

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1. Introduction

The recent discovery of graphene has opened a door to new vistas of low-dimensional physics [1]. The corresponding energy dispersion becomes the so-called Dirac cone, which leads to rich physics inherited from quantum electrodynamics. In terms of applications, the 2-dimensional (2D) sheet structure of graphene and its properties of ballistic transport and high mobility make graphene a promising candidate for future electronic devices. Nanostructures on graphene sheets can be fabricated by carving out of the graphene sheets directly, and the spread 2D sheet structure may open a door to realize the integrated quantum nano-device system. However, carriers in graphene (massless Dirac fermions) cannot be confined by an electrostatic potential due to Klein tunneling [2]. Therefore, in most cases, the formation of graphene quantum-dot (QD) devices relies on the removal of unwanted areas of graphene by etching, thereby resulting in devices with a geometrical confinement [3–5]. Although this top–down process enables precise control of graphene device structures on a submicron scale, the graphene-edge shape varies on a nanometer scale. Therefore, the transport properties of graphene QD or nanoribbon devices are often dominated by edge roughness and disorder. The performance of such devices is limited due to the detail of nanoconstriction structures. It is crucially important to develop other methods of creating graphene nanostructures and control the constriction. Recently, several bottom-up processes to fabricate nanoribbons have been developed that atomically control edge structure. But much research is still needed to develop fabrication processes capable of controlling the atomic-scale edge orientation for a given geometry.

In this paper, we proposed an alternative approach to confine the massless Dirac fermions in graphene. We fabricated the perfectly isolated graphene nano-islands, and contacted the electrodes directly to the graphene nano-structures with no constrictions. As discussed above, it is free from the disturbance due to the detail of constrictions. We discovered the evolution of the Coulomb oscillations under a magnetic field, i.e. 'magnetic-field-induced confinement', which leads to the transport spectroscopy.

2. Experiments

The graphene samples were prepared by micromechanical cleavage of Kish graphite deposited on the surface of a silicon substrate with a 90-nm-thick surface layer of oxidized silicon. From these samples, we selected a number of graphene flakes by optical microscope contrast and Raman spectroscopy measurements [6, 7]. Using these techniques, we confirmed that the samples used for the present study consisted of a single-layer graphene. The isolated graphene mesoscopic structures were patterned by electron-beam (EB) lithography using polymethyl-methacrylate (PMMA) resist as an etch mask, with O_2 reactive ion etching being used to etch away the unprotected graphene. Next, EB lithography was again used to deposit metal electrodes on the graphene mesoscopic structures to fabricate source and drain contacts. Figures 1(a) and 1(b) show schematic pictures of a designed graphene device. In this study, we designed the disk diameter is 550 nm, and the distance between contacts is L = 200 nm. A scanning electron microscopic image of the measured device is shown in the inset of Fig.1(c).

The fabricated devices were mounted in an ^{3}He cryostat equipped with a superconducting magnet. A magnetic field (B) was applied perpendicular to the sample chip. A highly-p-doped Si substrate was used to apply the back-gate voltage. All electrical-transport measurements were carried out at base temperatures of 0.23–1.7 K. The source-drain current (I) through the graphene device was measured as a function of the back-gate voltage (V_g) by applying a fixed DC bias voltage (V_{sd}).

Figure 1(c) shows the current through the graphene mesoscopic device as a function of V_g at B = 0 T and T = 1.7 K. The current curve is asymmetric and V-shaped with fluctuations. It has a broad minimum around the Dirac point at $V_g = V_{Dirac} \sim +4$ V. This asymmetry and shift in the gate voltage of the Dirac-point energy have been reported in previous studies and is referred to as the 'hole-doping case'. It has been interpreted as resulting from pinning of the graphene hole-carrier density under the metal and the formation of the surface electrostatic-potential by charge transfer across the metal/graphene junction [8, 9].

Figure 2 shows how the current evolves in a magnetic field as a function of V_g and B, at $T = 0.23$ K. Near the Dirac point, conductance is strongly suppressed by the magnetic field. Furthermore, several resonance peaks emerge in the hole- and electron-carrier regions. In particular, clear resonance peaks are observed in the hole-carrier region ($V_g < V_{Dirac}$). These peaks correspond to the Coulomb-blockade oscillations. As discussed in Ref. [10], such a quantum confinement-deconfinement transition is corresponding to the transition between open-to-closed trajectories of Dirac particles in this type of device structure. All trajectories are open for a sufficiently weak magnetic field, which corresponds to a continuum spectrum. At high magnetic fields, closed orbits emerge that correspond to quasi-bound states and coexist with open trajectories. Moreover, the quasi-bound states should be consistent with the Bohr–Sommerfeld condition [10–12] and lead to a discrete energy spectrum. In addition to that, tunnelling between open and closed trajectories leads to a finite resonance lifetime and QD formation. Resonance shapes are governed by charging effects via Coulomb blockade.

3. Summary

We proposed a graphene device structure that is not disturbed by structural fluctuations of constrictions and that is directly connected to the mesoscopic graphene system. With this device structure, we demonstrated that the Coulomb blockade evolves under a uniform magnetic field perpendicular to the graphene sheet. Our experimental results indicate that a quantum confinement–deconfinement transition is controlled by the magnetic field.

Acknowledgements

This study was supported by a Grant-in-Aid for Scientific Research (B), a Grant-in-Aid for Young Scientists (B), a Grant-in-Aid for Exploratory Research, the Nanotechnology Network Program, and the World Premier International Research Center Initiative on Materials Nanoarchitectonics from the Japan Ministry of Education, Culture, Sports, Science and Technology.

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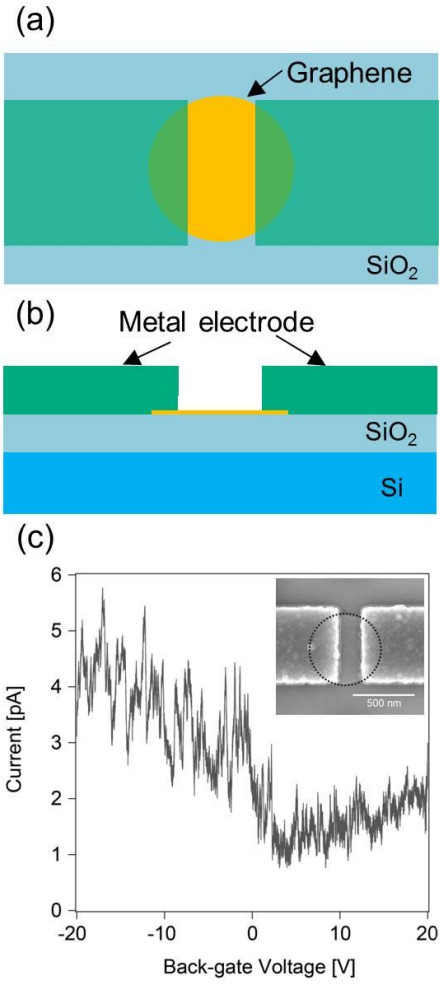

Fig.1. (a) Schematic picture of a designed graphene device. (b) A side-view schematic of the device. (c) Current through the device as a function of V_g at $V_{sd} = 100$ μV, $B = 0$ T and $T = 1.7$ K. Inset. A scanning electron microscopic image of the measured device. The patterned graphene mesoscopic structure is in the dashed-black circle.

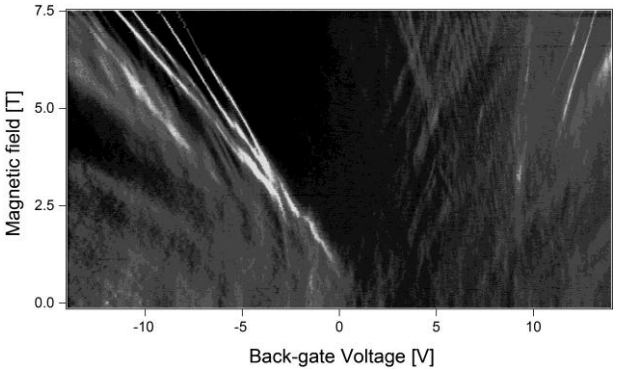

Fig.2. A gray scale plot of the current (for $V_{sd} = 500$ μV) as a function of V_g and B at $T = 0.23$ K. White and black regions correspond to a current of less than 15pA and more than 40 pA, respectively.