Electron Transport in Graphene with One-dimensional Local Strain

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1. Introduction

Graphene, a two-dimensional honeycomb lattice of carbon atoms, is a zero-gap semiconductor, having a linear dispersion relation at low energies, in which the conical valence and conduction bands touch each other at the top of the cones (Dirac cones). Because of such characteristic band structure, carriers (electrons and holes) in graphene behave as massless Dirac fermions, leading to unconventional “relativistic” phenomena occurring even in solid state materials. Besides, graphene is expected to be a promising candidate for the next-generation electronic materials due to its high mobility and strong electric field effect.

For application of graphene to electronics, especially to field effect transistors (FETs), the absence of a band gap is the biggest problem. The leading method for forming band gaps is electron confinement in graphene thin wires, called nanoribbons[1]. However, it has been revealed that real-world (experimental) nanoribbons have a serious technical issue; disorder of atomic arrangement in edges of nanoribbons causes electron reflection and even the Coulomb-blockade effect, severely deteriorating the mobility of graphene FETs[2]. Thus, the problem of band gap formation in graphene remains unsolved.

In 2009, a new method for the band gap formation in graphene using lattice strain was proposed, which made use of a Dirac fermionic property of graphene that lattice strain induces an effective gauge field[3]. It was theoretically shown that a strain field, $u_{ij}(x,y)$, in graphene lattice leads to a gauge field,

$$ A = \frac{\beta}{a} \begin{pmatrix} u_{xx} - u_{yy} \\ -2u_{xy} \end{pmatrix} $$

where $a$ is the lattice constant, $\beta$ is a function of the nearest neighbor hopping amplitude, and the $x$-axis is chosen along a zigzag direction of the graphene lattice[5]. This vector potential causes a lateral shift of the Dirac cone, $p$-$eA$, in the momentum space. For example, in graphene stretched in $y$-direction (see region B in Fig. 1(a)), the Dirac cone shifts along $k_y$-direction (Fig. 1(b)). When strained and unstrained graphene portions (region B and region A(C), respectively) are connected to form graphene with one-dimensional local strain, as shown in Fig. 1(a), conservation of $k_y$ at the interface leads to perfect reflection of electrons at low energies where Fermi circles of regions B and A(C) do not overlap, resulting in a transport gap at low energies.

For the experimental realization of graphene with one-dimensional local strain, we inserted a one-dimensional resist bar between the graphene film and the substrate, as shown in Fig. 2(a). In the sample fabrication, we first make a graphene device with electrodes on a Si/SiO$_2$ substrate covered with e-beam resist LOR (Fig. 2(b)) using standard e-beam lithography and lift-off. Then, the pattern for the resist bar is transferred to the LOR resist with an excess e-beam dose, which makes the LOR resist insoluble in its developers and removers (Fig. 2(c)). After the LOR resist without the excess e-beam exposure is removed by the remover, the graphene device is attached to the Si/SiO$_2$ substrate (Fig. 2(d)).

We confirmed formation of local strain by two methods; one is the micro Raman spectroscopy and the other is the change in the separation of resist dots placed on the graphene film (not shown). Figure 3(a) shows a grayscale plot of the spatial variation in wave number of the peak of Raman 2D band. Here, the white (black) areas correspond to 2D bands with large (small) wave number. As shown in Fig. 3(b), for areas around the resist bars, the wave number of 2D peak is located at 2661 cm$^{-1}$, while at the midpoint of adjacent resist bars, the peak is at 2644 cm$^{-1}$, indicating that the graphene film is strained more strongly as the distance from the resist bar increases.
3. Electron transport in strained graphene

For verification of the modulation of electron transport by strain, we compare the gate voltage ($V_g$) dependence of the conductivity ($\sigma$) in graphene devices with and without one-dimensional local strain made out of the same graphene film. Here, the back gate voltage is applied through a highly doped Si substrate.

The result is shown in Fig. 4, in which the blue (red) curve corresponds to the strained (unstrained) graphene. We find that in strained graphene the $\sigma-V_g$ curve exhibits an almost flat region at low conductivity area, while at high conductivity area the slope of the $\sigma-V_g$ curve (the field effect mobility) is close to that of the unstrained graphene. The similar behavior has been observed in many other samples. However, transport gap with zero conductivity has never been observed. One of the possible origins of the missing transport gap is the spatial fluctuations of the electric potentials induced by charged impurities, indicating that not only the method for controlling the strain but also the technique for cleaning the graphene surface become important issues.

4. Summary

Aiming at formation of transport gaps in graphene, we have developed a technique for inducing one-dimensional local strain in graphene. We observed modulation of conductivity by strain, however, the transport gap was not confirmed. In the future experiment, we are planning to clean the graphene surface and to enhance the strain for the formation of the transport gap.

References