Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp179-180

D-1-01(Invited)

Quantum Transport in van der Waals Junctions of Graphene and 2D Materials

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Abstract

We present our recent experiments on quantum transport in van der Waals junctions of graphene and 2D materials. In particular, we discuss the manipulation of ballistic carriers in graphene pnp junctions and the observation of Josephson effect in van der Waals junctions of layered superconductors.

1. Introduction

Recent advances in transfer techniques of atomic layers have enabled one to fabricate van der Waals junctions of two-dimensional (2D) crystals such as graphene, hexagonal boron nitride (h-BN), and transition-metal dichalcogenides (TMDs). Here, we present our recent experiments on quantum transport in van der Waals junctions of graphene and 2D materials [1-14]. In particular, we discuss the manipulation of ballistic carriers in graphene pnp junctions [1,2] and the observation of Josephson effect in van der Waals junctions of layered superconductors [3].

2. Ballistic graphene sawtooth-shaped npn junctions

Development of fabrication methods for high-mobility graphene/h-BN [15–18] has recently unveiled ballistic carrier-transport phenomena in graphene such as negative bend resistance [18,19], the magnetic focusing effect [5, 20, 21], and a magnetoresistance peak due to the boundary scattering [6]. Under such a ballistic carrier-transport regime, transmission of carriers can be described by analogy to the geometrical optics of light, opening up a research field of “Dirac fermion optics” [22]. Indeed, by using reflection and refraction of ballistic Dirac fermions at an interface of different carrier-density regions, especially at a pn interface, numerous characteristic functionalities have been realized experimentally [4,23-25]. More recently, systematic experimental studies about Snell’s law at ballistic graphene pn junctions was also reported [26]. In these systems, the pn interface can be utilized as an optical component between different refractive-index regions, e.g. lens, mirror, or prism.

Ballistic carrier transport has also been proposed as a tool to turn currents ON and OFF in graphene without inducing energy gap [27–31]. In particular, collimation and total reflection of ballistic carriers in tilted npn junctions were used as a method of suppressing ballistic carrier transmission in graphene [27,30,31]. The method has advantages for microwave electronics because the OFF state can be realized at high carrier density region without degrading graphene’s carrier mobility by using Dirac fermion optics, which is totally different from conventional ways such as making nanoribbons [32] and embedding defects [33].

Here, we demonstrate resistance enhancement in sawtooth-shaped npn junctions using collimation and total reflection of ballistic carriers. The tunable reflectance of ballistic carriers is a key ingredient of FET that had been proposed in Ref. [27,30,31], and could be an elementary—but important—step for realizing ultrahigh-mobility graphene field effect transistors utilizing Dirac fermion optics.

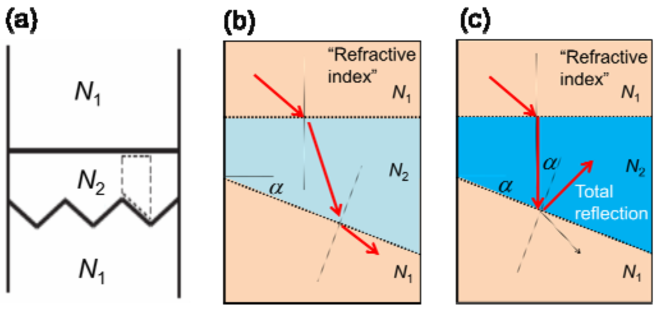

Fig. 1 (a) Schematic of zigzag-shaped npn junctions. (b, c) Schematic of mechanism of this device shown in the elementary unit of this device as depicted in dashed region in (a). Each represents (b) ON state at $N_1 < N_2$ and (c) OFF state at $N_1 << N_2$.

3. van der Waals Josephson junctions

Here, we demonstrate that a high-quality Josephson junction can be built simply by connecting two exfoliated flakes of layered 2D superconductor via van der Waals force. In the coherent transport of Cooper pairs through the $NbSe_2/NbSe_2$ van der Waals junctions, the following distinctive features were observed. (i) Current-voltage characteristics shows hysteretic zero-bias current, indicating the under-damped Josephson effect. (ii) The observed critical current density of 6600 A/cm^2 is comparable to the value used in modern Josephson junctions for single flux quantum circuits. (iii) Application of an in-plane magnetic field induces a periodic modulation of the critical current due to the phase shift in supercurrent, Fraunhofer pattern, which can be observed only when a well-defined cavity is formed in the Josephson junction. (iv) Coherent coupling between ac-Josephson current and electromagnetic wave within the junction gives Fiske resonance mode. (iv) The value of RNIc is as large as 1.04 mV, which is close to the maximum value expected from the Ambegaokar-Baratoff theory. All of those features evidences high quality of the vdW Josephson junctions in the present study. This has been achieved by eliminating all the heat treatment during junction fabrication to minimize the surface oxidation of 2D layered crystals. Our results suggest that a superconducting 2D material can be included as a new element to inject supercurrent into van der Waals superlattices of various 2D materials.

Acknowledgements

This work was partly supported by CREST, Japan Science and Technology Agency (JST); the Grant-in-Aid for Scientific Research on Innovative Areas "Science of Atomic Layers", "Topological Materials Science", and "Nano Spin Conversion Science" from the Ministry of Education, Culture, Sports, Science and Technology (MEXT); the Project for Developing Innovation Systems of MEXT; the Grants-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (JSPS). The research leading to these results have received partial funding from the European union Seventh Framework programme under grant nº 604391 Graphene Flagship. S. Morikawa acknowledges the JSPS Research Fellowship for Young Scientists.

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