Graphene p-n Junction as an Electronic Beam Splitter

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Abstract

N-type and p-type regions in graphene can adjoin without a gap in between. This article explains how such characteristic p-n junctions can serve as beam splitters of electrons. Utilizing the long coherence length of electrons in graphene may make it possible to carry out an electron version of quantum optics.

Keywords: graphene, p-n junction, electron beam splitter

1. Introduction

Quantum optics is a field of research that investigates the wave-particle nature of light based on quantum mechanics, using interferometers consisting of optical elements such as mirrors and beam splitters. Knowledge obtained from quantum optics has been applied to quantum cryptography and quantum teleportation. An electron is also a quantum having a wave-particle nature like a photon and can thus create interference. An important difference between an electron and a photon is whether it is a fermion or a boson. This difference appears in their two-particle interference.

Another important difference is the presence/absence of the Coulomb interaction. The presence of the Coulomb interaction for electrons has both positive and negative aspects; the electron quantum state can be controlled through the interaction, but its coherence is easily destroyed. The resulting short coherence length makes experiments on electron quantum optics difficult to carry out.

Thus far, electron quantum optics has been conducted in the quantum Hall effect regime, which appears under a magnetic field in two-dimensional electron systems formed in GaAs/AlGaAs (gallium arsenide/aluminium gallium arsenide) heterostructures. A narrow channel in these systems called a quantum point contact with an electron transmission probability of 1/2 (**Fig. 1(a)**) is used as a beam splitter. A fundamental problem with these systems is the short coherence length of about 10 μm, which is comparable to the typical size of interferometers, limiting experiments to the basic level. One way to solve this problem and carry out more advanced experiments is to use graphene, in which the coherence length is expected to be longer. However, since graphene is a gapless material, beam splitters based on quantum point contacts made by depleting local electrons do not work.

In this study, a team comprising members from NTT Basic Research Laboratories and CEA Saclay proposed a new beam splitter architecture using a graphene p-n junction and verified its performance. Electrons in graphene that are injected from the n and p regions are mixed in the p-n junction and then partitioned at the exit of the junction (**Fig. 1(b)**). The electron mixing and the subsequent partitioning processes can serve as a beam splitter. The behavior of the beam splitter was verified by measuring the current shot noise.

2. Device fabrication and measurements

Graphene is generally obtained by exfoliating it from graphite. A drawback of this technique is that the graphene size is limited to several tens of micrometers. In contrast, the graphene we used was epitaxially grown by thermally decomposing the SiC (silicon carbide) substrate (**Fig. 2(a)**). SiC substrates were annealed at ~1800°C in Ar (argon) at a pressure of less than 100 Torr. For the device fabrication, graphene was etched in an O_2 (oxygen) atmosphere.

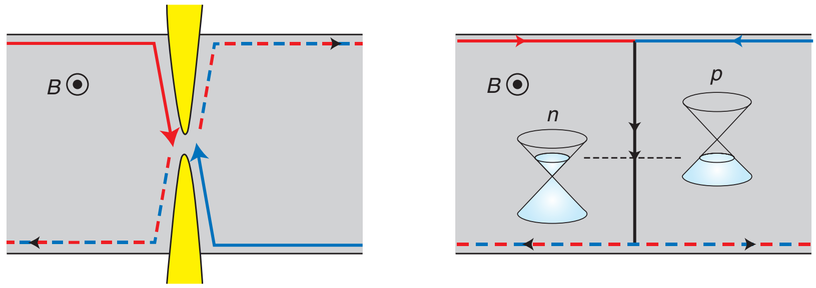

Fig. 1. (a) Quantum point contact (QPC) in a standard semiconductor device, formed by a pair of split gates (yellow). The transmission of the QPC is set to 0.5 so that electrons injected to the QPC are randomly transmitted or reflected to the downstream channels (red and blue dashed lines). (b) Graphene p-n junction. Current channels from the n and p regions (red and blue lines, respectively) are mixed in the p-n junction (thick black line) and then partitioned at the exit of the junction. Therefore, electrons injected to the p-n junction are randomly distributed to the downstream channels in the n and p regions (red and blue dashed lines).

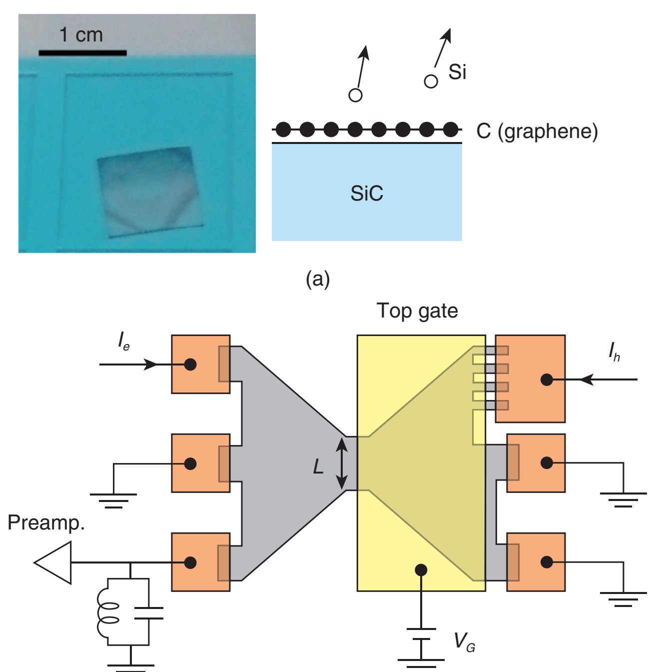

Fig. 2. ((a) left) Photograph of graphene grown on SiC. ((a) right) Schematic of graphene growth on SiC. (b) Device structure of graphene with a p-n junction. Gray region represents n-doped graphene. Tuning the bias of the top gate (yellow region) changes the carrier type in the gated region to a hole, and a p-n junction is formed at the interface between the gated and ungated regions. Orange regions are ohmic contacts.

After etching, the surface was covered with 100-nm-thick HSQ (hydrogen silsesquioxane) and 60-nm-thick SiO_2 (silicon dioxide) insulating layers. A p-n junction was made using a top gate covering half of the graphene. The ungated region was n doped, while p carriers were introduced in the gated region. Therefore, a p-n junction was formed at the interface between the gated and ungated regions (**Fig. 2(b)**).

We were able to fabricate devices with different p-n junction lengths between 5 and 100 μm by exploiting the wafer-size graphene.

All measurements were carried out in a quantum Hall effect regime, which was created by applying a magnetic field perpendicular to graphene at a low temperature of 4 K. The noise measurement involved converting the current noise into voltage fluctuations across one 2.5-kΩ resistor in series with the sample.

3. Behavior of graphene p-n junction as electron beam splitter

Current in the quantum Hall effect regime flows along the edge of the graphene in a direction determined by the polarity of the magnetic field and the carrier type (electron or hole). When a p-n junction is formed, counter-circulating edge channels of electrons and holes are mixed in the p-n junction and then partitioned at the exit of the junction. The mixing and the subsequent partitioning processes serve as an electron beam splitter; electrons injected from the electron channel are randomly distributed to the downstream electron and hole channels (Fig. 1(b)).

We tested the behavior of the beam splitter by measuring the current noise (shot noise) caused by the random electron distribution. The results demonstrate that the random partitioning noise is present when a p-n junction is formed (solid and open cyan circles) and absent when it is not (black circles), as shown in **Fig. 3**. We further found that the amplitude of noise increases as the p-n junction length decreases (**Fig. 4**). This indicates that the energy relaxation length of electrons in a p-n junction is 15 μm. The amplitude of noise in a short p-n junction is consistent with beam-splitter behavior.

4. Future work

The architecture of a graphene p-n junction is simpler than that of a quantum point contact, which is used as a beam splitter in conventional semiconductors. This allows us to integrate several beam splitters within a mesoscopic scale in graphene. Utilizing these beam splitters and long coherence length in graphene would make it possible to fabricate complicated electronic interferometers. Experiments on these devices would reveal the effects of the Coulomb interaction on decoherence. Furthermore, the generation of quantum entangled electron pairs is expected to be achieved in such devices.

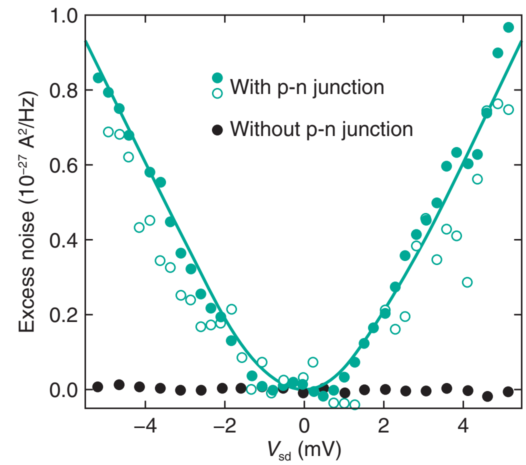

Fig. 3. Shot noise generated by p-n junction as a function of the bias applied to the electron channel V_{sd}. Solid cyan and black circles represent the measured noise in the presence and absence of p-n junctions. Open cyan circles represent the noise in the presence of a p-n junction obtained by applying bias to the hole channel.

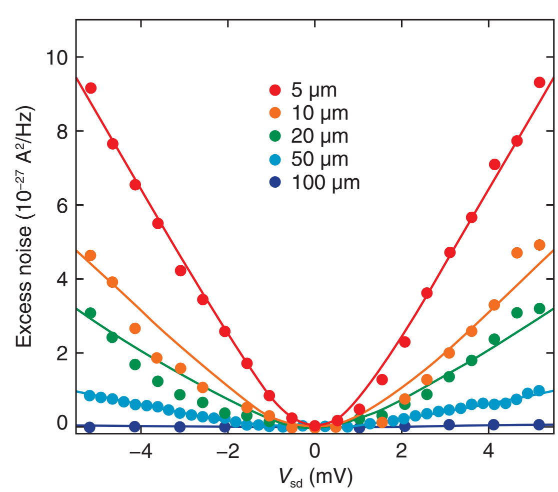

Fig. 4. Shot noise for different values of p-n junction length as a function of the bias applied to the electron channels V_{sd}.

This work was done in collaboration with NTT Basic Research Laboratories and CEA Saclay. Complementary results achieved by a group from Osaka University, Kyoto University, and the National Institute for Materials Science have been published simultaneously [2].

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