Development of superconducting interference device based on graphene

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Abstract. We fabricated and examined the operation of graphene-based superconducting interference device (SQUID) consisting of two superconductor-single layer graphene-superconductor junctions connected in parallel on a superconducting loop made of aluminum. Current-voltage characteristic of the device exhibits supercurrent flowing through SGS junctions. Mean switching current can be modulated with the applied magnetic field periodically. Deduced oscillation period coincides well with that estimated from the device geometry, suggesting that our device works as a graphene-based SQUID.

1. Introduction

Graphene is a two-dimensional sheet of carbon atoms experimentally discovered in 2004 [1]. In graphene, charge carriers have zero effective mass and exhibit high intrinsic mobility and saturation velocity [2]. Those exceptional properties make graphene special not only for practical electronic devices as an alternative material of silicon but also for fundamental research as a bench top experimental field of Dirac particles [3, 4].

When superconducting electrodes are connected with graphene, superconductivity can penetrate into graphene, which is called the superconducting proximity effect. Beenakker first predicted that unusual electron-hole conversion, specular Andreev reflection, occurs at graphene-superconductor interface as a consequence of the interplay of superconductivity and relativistic dynamics [5]. Experimentally, Heersche \textit{et al.} first reported that graphene can support supercurrent by the proximity effect [6]. They explained that the induced superconductivity in graphene can be modulated with the gate voltage. Girit \textit{et al.} applied this effect to fabricated a superconducting interference device (SQUID) based on graphene [7].

Here we report on the fabrication and operation of graphene-based SQUID made of two superconductor-monolayer graphene-superconductor (SGS) junctions. Mean switching current of the device exhibits a clear periodic oscillation as a function of the applied magnetic field,
which demonstrates successful operation of the device. Our device can be applied to fundamental studies on electron-hole conversion process in SG systems as well as to an extremely sensitive detector, such as a magnetometer for a micro defect in graphene or a nanomagnet adsorbed on graphene [7, 8].

2. Experimental

Our graphene-based SQUID, schematically shown in Fig. 1(a), consists of two superconductor/monolayer graphene/superconductor (SGS) junctions connected in parallel on a superconducting loop made of aluminum. The junction is designed to be 2 µm wide and 100 nm long. Loop size of the SQUID is 30 µm², which is expected to give \( \frac{h}{2e} \times 10^{-12} \sim 0.69 \) G period oscillation of the critical current.

The device was fabricated on a silicon substrate covered with a 290 nm thermally-grown SiO₂ layer. Graphene was prepared by micromechanical cleavage of kish graphite and transferred onto the substrate. Following the identification of graphene with the optical microscope, ZEP520A resist was spun onto the sample and electron-beam lithography (EBL) was performed to pattern the etching mask. We etched unnecessary parts of graphene by reactive ion etching (RIE) based on the O₂ plasma. After RIE, bonding pads made of Ti/Au (10/250 nm) was deposited by EBL and e-gun deposition. Finally superconducting lead made of Ti/Al/Ti (10/100/5 nm) was fabricated. Figure 1(b) shows the scanning electron microscope (SEM) image of an SGS junction. Actual junction length was about 70 nm. Raman spectrum of the junction region obtained with the Raman microscope is shown in Fig. 1(c). Two pronounced peaks, labeled G and D ⊥, can be seen. We identified graphene from their spectral shape and intensity ratio [9]. Note that we performed both SEM and Raman measurements after transport measurements to avoid possible disorder by electron beam or laser exposure [10, 11].

Samples were placed in the dilution refrigerator. We measured current-voltage (IV) characteristics of the SQUID as a function of the magnetic field applied perpendicular to the SQUID plane. Also differential resistance-bias voltage characteristics were measured by means of standard lock-in technique.
3. Results and discussions

Results of transport measurements on the SQUID #1216B87a are shown in Fig. 2. Figure 2(a) shows $dV/dI-V$ characteristic. Below $|V| = 0.2 \, \mu V$, the resistance is decreased compared to normal state resistance $\sim 200 \, \Omega$ and dips labeled $n=1, 2, 3$ can be seen at specific voltages. This is called subharmonic energy gap structure due to multiple Andreev reflection, which is a clear evidence of induced superconductivity in graphene by the superconducting proximity effect [12]. The dips appears at $V_n = 2\Delta_{Al}/ne$ ($n = 1, 2, ...$), which enables us to determine the superconducting energy gap $\Delta_{Al}$. We find $\Delta_{Al}=0.1 \, \text{mV}$, which is a reasonable value for our sample structure[6, 13].

Figure 2(b) illustrates $IV$ characteristic at $T=35 \, \text{mK}$. Josephson supercurrent flowing through SGS junction is observed. Switching current ($I_s$) is about 180 nA at back-gate voltage ($V_g$) = 0 V in the zero field. Also $IV$ curve shows hysteresis as expected for underdamped Josephson junctions in the resistively and capacitively shunted junction (RCSJ) model.

By applying magnetic fields, we examined the operation of the SQUID. Figure 2(c) shows $I_s$ as a function of the applied field. Periodical oscillation of $I_s$ whose period is about 0.7 G can be seen. This period well coincides with the expected period (0.69 G), which demonstrates that we succeed to develop graphene-based SQUID. Unfortunately we couldn’t apply $V_g$ at all to this SQUID because of a terrible leak current.

In the other device #1216D29a, we could apply the gate voltage and observe gate modulation of transport properties as shown in Fig. 3(a). Although the transition from superconducting to normal conducting state is smeared (Fig.3(a) inset) due to rather high measurement temperature ($T=0.6 \, \text{K}$), we confirmed its operation as a SQUID (not shown).

Finally, we consider mean free path ($l_m$) in our device. Figure 3(b) illustrates the resistance of the graphene channel of device #1216D29a as a function of $V_g$ at $T=4.2 \, \text{K}$. At this temperature, all of the electrodes are in the normal conducting state. Charge neutrality point (NP) is located at $V_g = -11 \, \text{V}$. Away from NP, where the random potential fluctuations due to substrate and impurities are well screened, $l_m$ can be deduced by using $l_m = \sigma h/2\varepsilon^2 k_F$ [14]. Here, $k_F = \sqrt{\varepsilon \varepsilon_0 V_g \pi/ed}$ is Fermi wavelength, where $d=290 \, \text{nm}$ and $\varepsilon \sim 4$ are the thickness of SiO$_2$ layer and its dielectric constant, respectively. Figure 3(c) shows deduced $l_m$, which is found only around 12 nm. This is much shorter than the junction length, so our device is in the diffusive transport regime. For further development of the device and exploration of superconductivity in graphene we have to fabricate SGS junctions with ballistic graphene by
Figure 3. Gate modulation of transport properties of the device #1216D29a. (a) Color plot of $IV$ characteristics as a function of $V_g$ at $T \sim 600$ mK. Inset: $IV$ curve at $V_g=0$ V. (b) Resistance of the graphene channel as a function of $V_g$ at $T=4.2$ K. (c) Mean free path in the channel deduced from its resistance.

applying other microfabrication techniques [15, 16].

4. Conclusion
In conclusion, we have developed graphene-based SQUID and examined its operation at low temperatures. Mean switching current shows periodical oscillation as a function of the applied field. Deduced oscillation period well coincides with our device design, which indicates successful operation of our device. On the other hand, mean free path in the graphene channel deduced from its conductivity is much shorter than the channel length. Fabrication of ballistic graphene channel is needed for further development of the device and its application.

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