Implementation and Observation of Highly Adjustable Bandgap in Bilayer Graphene based Dual-Gate Field-Effect Transistor

Group:B335 Supervisor: Prof. Chang-Hua Liu Members: Hao-Chun Liang

Abstract

Many modern products heavily rely on semiconductor materials as their foundational technology. Within this realm, the bandgap stands out as a crucial parameter for the design of devices and circuits. Nonetheless, designers of devices and analog circuits frequently grapple with constraints stemming from the inability to modify a material's bandgap, which significantly restricting design flexibility. Nevertheless, bilayer graphene has unique physical properties, and an external electric field can regulate its bandgap, allowing for control within a range of up to 250 meV. This offers a remarkable degree of design flexibility. This project involves the application of a dry separation method to extract thin slices of materials. We will collect samples with shapes and thicknesses that align with the project's design criteria under an optical microscope. These samples will serve as the building blocks for the creation of a Dual-Gate Bilayer Graphene Field-Effect Transistor. Subsequent testing, including the examination of I-V curves and two-dimensional current measurements between V_{top} and V_{bottom}, will be conducted to thoroughly investigate the properties of the bilayer graphene.

Implementation

Sample fabrication involves using a diamond knife to cut a silicon wafer into a predetermined shape. Next, a series of necessary materials such as bismuth silicate (Bi_2SiO_5), graphene, and boron nitride (BN) are picked up with tweezers and placed on tape. After a repeated peeling process, these materials are evenly distributed within the specified area of the tape. The tape with the attached materials is then gently adhered to the preselected silicon wafer, placed on a heating plate with a glass slide as a substrate and heated uniformly. After a cooling period of thirty minutes, the tape is gently peeled off, completing the sample fabrication. The second step involves creating a schematic design. Initially, the samples are carefully examined under an optical microscope, and photographs of all available samples are taken using a camera attached to the microscope. These images are then organized and archived into specific folders. After collecting sample images, presentation software is used to create a schematic design, as shown in Fig. 1.

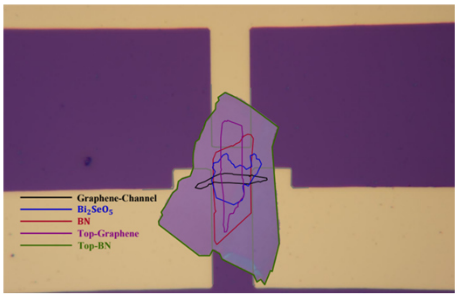

Fig. 1 The schematic design drawn from existing samples.

According to the schematic design and following the laboratory process for component fabrication, the next step is to place the components into a vacuum chamber and tightly connect them to the measurement pins above. Subsequently, various measurements can be conducted by applying input voltage to the corresponding points on the components, controlled through LabVIEW.

Result

If we perform channel current-upper gate bias measurements for multiple back gate biases, we can obtain Fig. 3. Each curve of channel current-upper gate bias for each back gate bias will exhibit a minimum current point as shown in Fig. 2, representing the neutral point position corresponding to each back gate bias. Overall, through the observation of current-upper gate bias measurement curves for multiple back gate biases, an important trend can be noted: as the average value of the D-field gradually increases, the resistance value of the neutral point also rises, while the current

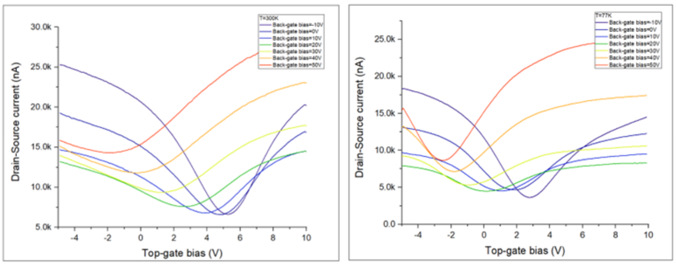

Fig. 2 The measurement of D-field modulation in the device.

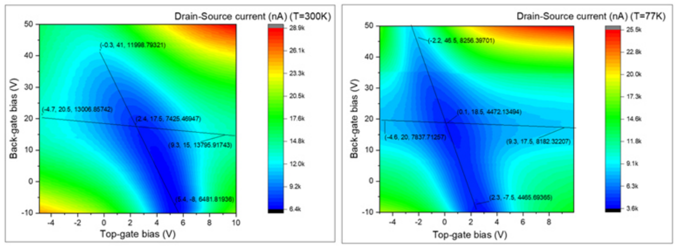

Fig. 3 Measurement of the two-dimensional current map for the device with back gate-upper gate bias.

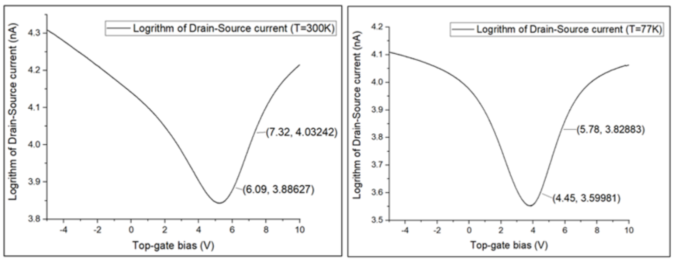

Fig. 4 Subthreshold swing determination

value decreases. This phenomenon arises due to the gradual widening of the bandgap in bilayer graphene. On the other hand, the sub-threshold swing (S) is defined by the following formula, where ψ_s represents the surface potential, used to measure the rate at which a field-effect transistor opens and closes its channel through gate control.

$$S \overset{\text{def}}{=} \frac{dV_G}{d(\log_{10} I_D)} = \frac{kT}{q} \times \ln 10 \times \frac{dV_g}{d\psi_s}$$

For the case of mixed upper gate bias, the channel current is plotted on a logarithmic scale, and a suitable region for fitting a straight line is found near the neutral point, resulting in Fig. 4. The sub-threshold swing is found to be 8.416 at room temperature and 5.81 at liquid nitrogen temperature, validating that the sub-threshold swing is indeed lower at lower temperatures.

Conclusion

Graphene possesses unique linear energy-momentum relationship and Dirac cone-shaped band structure, endowing it with high electron mobility and corresponding high conductivity. Subsequently, the mean and difference values of the upward and downward electric fields generated by the upper gate and back gate, respectively, will influence the band structure of the bilayer graphene channel. This causes an enlargement of the bandgap and induces doping effects. Through measurements of the two-dimensional current values between the upper gate bias and back gate bias, we can identify the neutral point corresponding to the compensation voltages V_{b0} and V_{t0}. Finally, by outwardly searching for the neutral point with no bandgap as the center, an increasing resistance is observed. It can be concluded that the bandgap of bilayer graphene can indeed be opened due to the breaking of lattice symmetry by the electric field. Due to the presence of sub-threshold oscillations, the bandgap opened at low temperatures can more effectively close the bilayer graphene channel.

[1] Zhang, Y., Tang, TT., Girit, C. et al. Direct observation of a widely tunable bandgap in bilayer graphene. Nature 459, 820–823 (2009). https://doi.org/10.1038/nature08105