Quantum Transport in Patterned Graphene Nanoribbons

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Graphene, a single sheet of graphite, has aroused intense interest since its isolation in 2004. Two-dimensional (2D) graphene sheets are nearly metallic, while ultrathin graphene nanoribbons (GNRs) show semiconducting properties with the energy bandgap scaling inversely with the ribbon width. Although sub-10-nm GNRs have been achieved by chemical approaches [1, 2], the ability to form GNRs lithographically will facilitate the compatibility with the conventional planar integrated circuit (IC) manufacturing. Hydrogen silsesquioxane (HSQ) is widely utilized as etching masks to fabricate GNRs due to its high resolution in e-beam lithography (EBL). HSQ can be removed by buffered hydrofluoric (BHF) acid after the GNR formation. However, the normally used SiO_2 substrate supporting the exfoliated graphene can be etched by BHF as well. In this work we present the fabrication of GNRs using Al metal mask in the O_2 plasma etching. GNRs as thin as ~ 20 nm have been achieved. The conductance modulation by the back gate is in the order of 10^6 at 4.2 K. Besides, quantized conductance was observed in the thin GNRs which form quasi-1D transport systems due to the carrier constriction by the ribbon edge boundaries. Landauer's formula was applied to fit the experimental data and excellent agreement was achieved.

GNRs were fabricated on exfoliated graphene flakes on SiO_2/Si. The oxide thickness is 300 nm and the Si substrate is heavily doped n-type. Al metal masks were patterned by EBL and e-beam deposition. The exposed graphene was removed by O_2 plasma etching and then the metal masks were removed by Al etchant. GNRs connected to two 2D graphene sheets were thus achieved. Fig. 1 shows the SEM images of a 29 nm wide Al mask ribbon (top) and a 21 nm wide GNR (bottom). The fact that the obtained GNR is thinner than the Al mask indicates the effect of lateral etching in O_2 plasma. Cr/Au was e-beam deposited as source (drain) contacts on the 2D graphene areas to reduce the contact resistance. Al/Au was used as the back-gate contact. Fig. 2 shows the detailed device structure. The length of GNRs in this work is 2 μm. Current-voltage (I-V) measurements were performed in vacuum (~ 10^{-6} Torr) with temperature ranging from 4.2 K to 300 K.

The temperature dependent transfer characteristics at V_{ds} = 20 mV are shown in Fig. 3. It can be seen that the minimum current decreases with decreasing temperature and the back-gate modulation increases from ~ 10 at room temperature to > 10^6 at 4.2 K, indicating the formation of energy bandgap. The hole conduction is much larger than the electron conduction, most probably due to some surface impurities. But the exact origin remains unclear currently. Fig. 4 shows the family I-Vs measured at 77 K. The drain current exhibits tendency to saturate at high drain bias and the maximum current density is ~ 1.4 A/mm. Quantized conductance was seen at low temperature and Fig. 5 shows a typical conductance-gate curve with roughly equally spaced plateaus. The experimental data were fitted using Landauer's formula and excellent agreement was achieved as shown in Fig. 6. The obtained subband energy separation from the fitting is 28 meV, close to the value (34 meV) calculated from the GNR band structure [3] for W = 20 nm. The average transmission probability (t) is ~ 0.02, similar to that reported in [4]. The very small t can be explained by the scattering due to GNR edge/bulk disorders [5].

References

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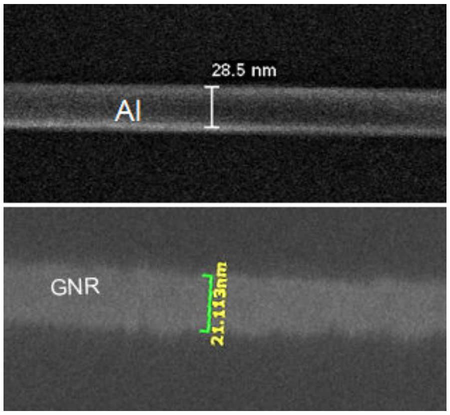

Fig. 1 SEM images of an Al mask strip (top) and a GNR (bottom).

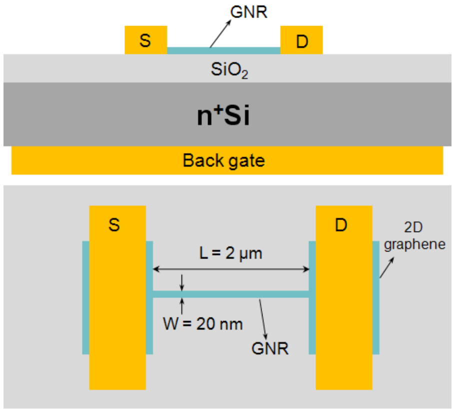

Fig. 2 Cross-section (top) and top view (bottom) of the device structures.

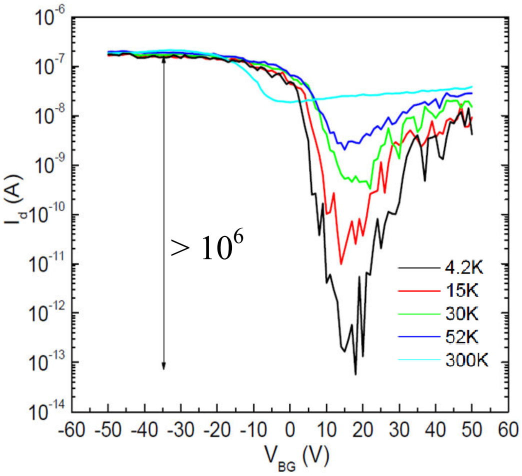

Fig. 3 Temperature dependent GNR transfer characteristics at $V_{ds} = 20$ mV.

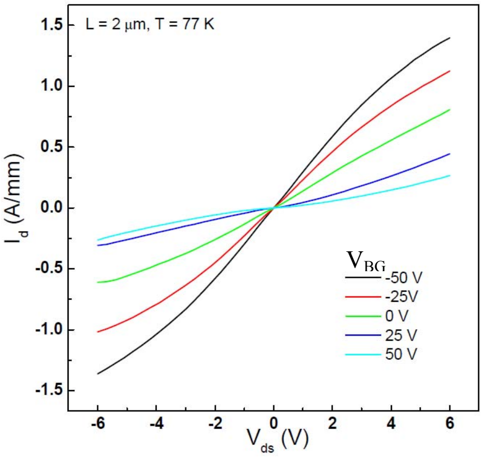

Fig. 4 GNR family I-Vs at 77 K, showing tendency to saturate.

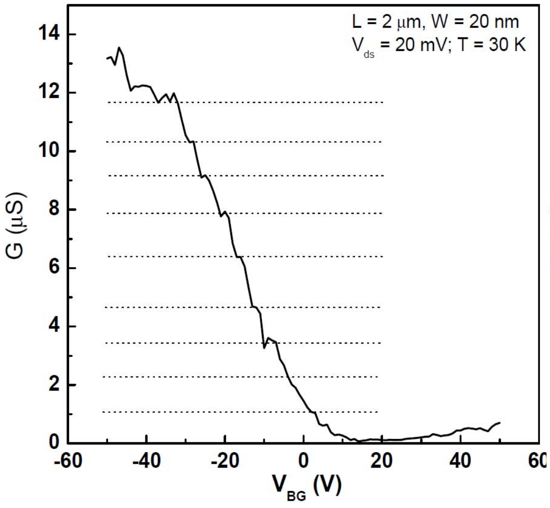

Fig. 5 Conductance quantization in a 20 nm wide GNR.

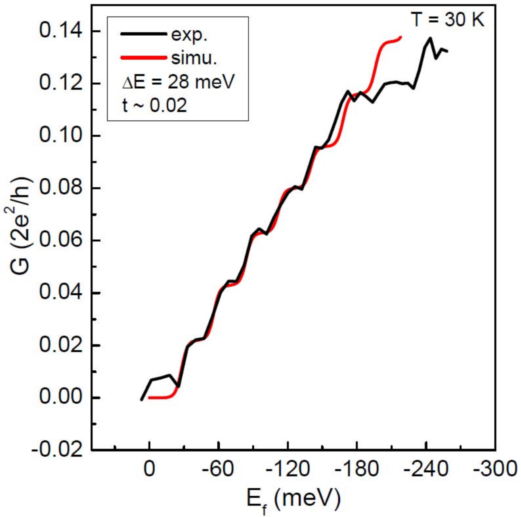

Fig. 6 Data fitting using Landauer's formula, showing excellent agreement between the model and the experimental data.