BAPVC Annual Project Report

Project Title: Graphene Electrode Engineering for Photovoltaic Applications
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Summary: The UCSB group has achieved the growth of wafer-scale few-layer graphene (FLG)[1]. They have also experimentally demonstrated intercalation doping (with $FeCl_3$) and surface doping of FLG guided by density functional theory (DFT) calculations to further reduce sheet resistance of 2 to 4-layer graphene. After intercalation doping by $FeCl_3$, 3-layer graphene exhibited a sheet resistance of 40 Ω/□ ,while 4-layer graphene has even smaller sheet resistance of 20 Ω/□, which is the smallest value achieved till date compared with any reported results.

Key Accomplishments:

1. **Growth of large-scale and high-quality few-layer graphene by catalyst engineering**

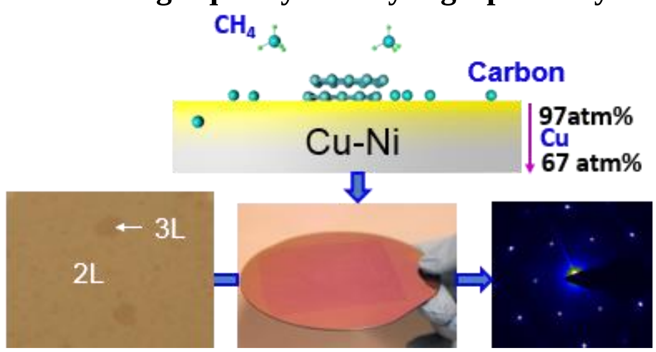

Figure 1. Demonstration of few-layer graphene growth on Cu-Ni alloy in a controllable manner.

The UCSB group found that wafer-scale few-layer graphene can be grown via chemical vapor deposition (CVD) on Cu-Ni alloy surface by a surface catalytic mode, in which carbon diffusion into bulk Cu-Ni alloy can be made negligible via optimal stoichiometry of the Cu-Ni substrate, thereby leading to the growth of 2-4 layer graphene as shown in **Fig.1**. The synthesized few-layer graphene exhibits high quality (mobility), which is comparable to that of exfoliated samples.

2. **Developing graphene doping techniques**

The UCSB group has theoretically and experimentally studied surface charge transfer doping[2], substrate doping[3] and intercalation doping of FLG. Their study revealed that intercalation doping (**Fig.2a**) is the most efficient and stable doping method. The theoretical calculations showed that $FeCl_3$ is a good dopant to reduce sheet resistance of FLG (**Fig.2b**). They developed a simple vapor transfer method to dope graphene. The successful doping was confirmed by the Raman spectra (**Fig.2c, d**) as well as the sheet resistance (**Fig.2e, f**). After doping, graphene shows p-type conducting behavior (upper green line in **Fig.2e**) and its conductance is significantly enhanced compared with that of the undoped graphene (lower line with V shape in **Fig.2f**). CVD graphene exhibited similar quality with respect to the exfoliated graphene as indicated by the similar sheet resistance (black and red line in **Fig.2f**). 3-layer graphene exhibited a sheet resistance of 40 Ω/□, while 4 layer graphene has even smaller sheet resistance of 20 Ω/□, which is the smallest value reported compared with any reported values till date (**Fig.3**).

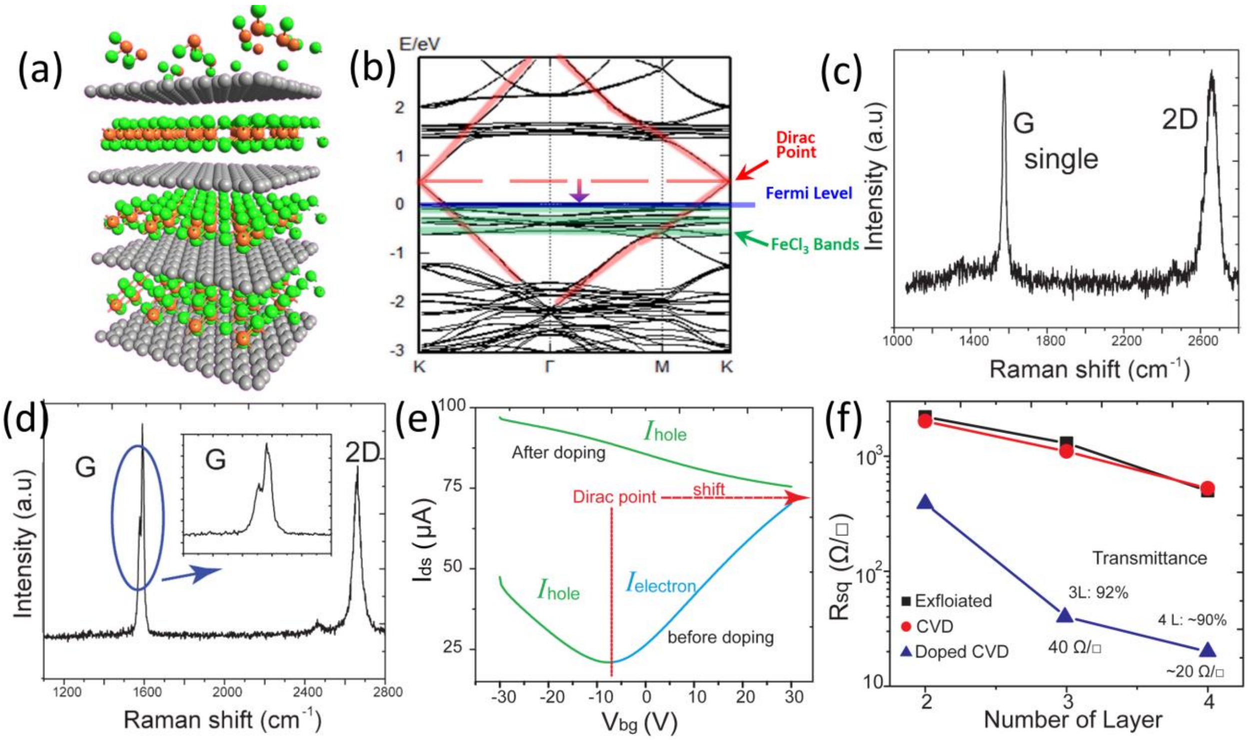

Figure 2. (a) Schematic illustration of FLG with $FeCl_3$ intercalation doping. (b) Band structure of intercalated bilayer graphene. Raman spectra of (c) trilayer graphene and (d) trilayer graphene with $FeCl_3$ intercalation doping. (e) I-V characteristics of back-gated FET showing intercalation doping effect. (f) Sheet resistance/transmittance of undoped graphene (black and red lines) and doped graphene (blue).

Future Work:

UCSB group intends to optimize intercalation doping ($FeCl_3$) and surface doping mechanisms guided by DFT to further reduce the sheet resistance of 2 to 4-layer graphene. They will also explore additional doping methods to further reduce sheet resistance to below 10 Ω/□ with high transmittance by patterning metal grids (or metal nanowire) on top of intercalation doped FLG. Finally, they will also explore the reliability of doped FLG. The current reliability test indicates that doped FLG does not degrade in ~half year.

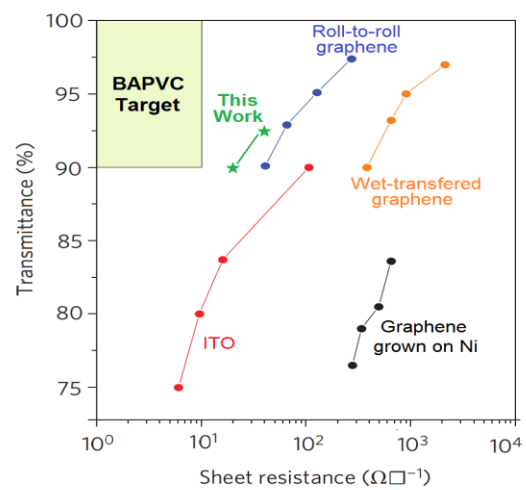

Figure 3. Comparison of sheet resistance and transmittance obtained from this work at UCSB and other results in the literature.

References:

1. Liu, W.; Kraemer, S.; Sarkar, D.; Li, H.; Ajayan, P. M.; Banerjee, K. *Chemistry of Materials*, Vol. 26, pp. 907-915, 2013.
2. Khatami, Y.; Liu, W.; Kang, J.; Banerjee, K. *Proc. SPIE 8824, Next Generation (Nano) Photonic and Cell Technologies for Solar Energy Conversion IV*, 88240T, September 25, 2013.
3. Khatami, Y.; Li, H.; Liu, W.; Banerjee, K., *IEEE Transactions on Nanotechnology*, Vol. 13, No. 1, pp. 94-100, 2014.