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# Manual turbostratic stacked graphene transistor: A study on electrical properties and device potential

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ABSTRACT

This study investigated the potential of turbostratic stacking of graphene few-layers produced using the consecutive electrochemical delamination method for electronic applications. The temperature dependence of electrical conductivity was measured to identify the transport mechanisms and band overlap. By lowering the temperature from 298 to 20 K, it was shown that these highly disordered structures follow nearest neighbor hopping through the variable range hopping mechanism. Variations in band overlap for samples versus carrier concentration were extracted and show that trilayer graphene has the best electrical properties at a mobility of about 1000 $cm^2/V\,s$ and the lowest band overlap at 28.5 meV which is promising structure for optoelectronic applications.



## 1. Introduction

Graphene is a mono-layer two-dimensional semi-metal where the valence and conduction bands touch at the Dirac points at the border of the Brillouin zone [1–3]. This material has remarkable electronic [4,5], optical and mechanical properties which can be used in a new generation of devices [6,7]. For instance, the high mobility of charge carriers has attracted considerable interest in high-speed electronics [8]. High carrier mobility, optical transparency, broad band response are promising properties of graphene for future (opto)-electronics applications, including integrated circuits [9], heterojunctions with 2D and 3D semiconductors [10,11], transparent electrodes and channel material for field effect transistors, displays and sensors [12]. These characteristics can be improved for optoelectronic applications using multilayer graphene (MLG) to enhance absorption of light, providing that MLG still preserves many of appealing properties of single layer graphene. MLG presents in an oriented stack and may present turbostratic disorder as either complete with all layers disoriented or partial. For example, a twisted trilayer was found experimentally on SiC-grown samples, on graphene on graphite and as exfoliated few-layer graphene (FLG) [14]. The FLG grown on SiC has shown nearly ideal band structure [15], like single layer graphene [16–18]. The electronic properties of FLGs are strongly dependent on the stacking arrangement and the number of layers [14,19]. Rotational disorder in stacking has been determined experimentally and theoretically [14]. A bilayer is a semiconductor with a gate-tunable band gap [14,20–22]; a trilayer is semi-metal with a gate-tunable overlap between the conduction and valence bands [23–25].

MLG is the most energetically-favorable structure, but there is a lack of fundamental study on the nature of multilayer disordered graphene devices and their potential in device applications [13]. Fuhrer et al. [26] reported on a transport mechanism for exfoliated bilayer graphene and found that Efros-Shklovskii and Mott variable range hopping (ES and Mott VRH) dominated at low temperatures (below 100 K). Their study found that the thermal activation conduction (TAC) mechanism occurred at above 100 K, but there was no nearest neighbor hopping (NNH) mechanism in this orderly exfoliated structure. A disordered graphene structures also can be produced by doping. Craciun et al. [25] observed a transition from electronic transport through Mott-VRH to ES-VRH at less than 125 K for exfoliated mono-layer samples doped with fluorine. Mott-VRH transport appears in exfoliated multilayer fluorinated graphene with a high concentration of fluorine. Generally, changes in the transition temperature range occur in response to changes in the structure from well-ordered to disordered by natural or manual preparations or doping.

Most potential applications require large-scale production of graphene layers [27]. Although mechanical exfoliation of graphite produces the best-performing samples, the manual effort yields unreliable, random and small areas which hinder practical applications. Other synthesis methods include epitaxial growth on SiC and chemical vapor depositions (CVD) on single-crystalline metals, but these are costly methods with expensive substrates. CVD on polycrystalline foils can produce cost-effective wafer-scale graphene [28]. Our suggestion for economical and easy method of few-layer preparation is consecutive

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transfer of CVD graphene on substrate. Because this manual turbostratic FLG has unknown physical properties, the present study provides a systematic study of the fundamental electronic properties of disordered FLG prepared using the consecutive electrochemical delamination transfer method. The study corresponds to density and temperature dependent carrier electrical transport and carrier transport mechanisms in back-gated graphene structures. The mobility obtained with this method is higher (1000 $cm^2/V\,s$) for trilayer graphene than for FETs (300–400 $cm^2/V\,s$) [29] using the growth of MLG with a turbostratic structure.

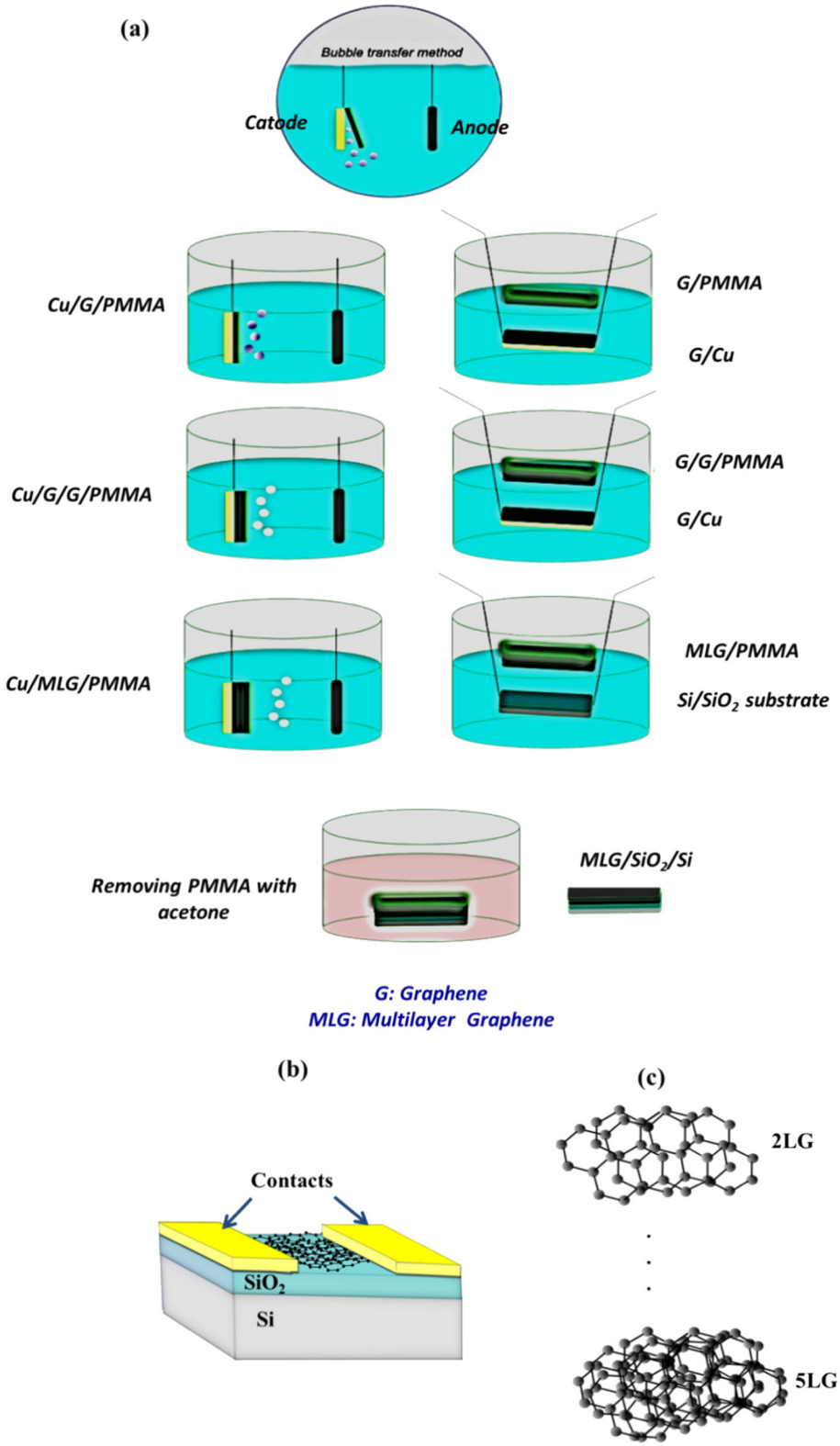


**Fig. 1.** (a) Consecutive bubble transfer method; (b) device schematic; (c) transferred turbostratic structure.