Electrical transport in suspended and double gated trilayer graphene

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We present a fabrication process for high quality suspended and double gated trilayer graphene devices. The electrical transport measurements in these transistors reveal a high charge carrier mobility (higher than 20000cm$^2$/Vs) and ballistic electric transport on a scale larger than 200nm. We report a particularly large on/off ratio of the current in ABC-stacked trilayers, up to 250 for an average electric displacement of -0.08 V/nm, compatible with an electric field induced energy gap. The high quality of these devices is also demonstrated by the appearance of quantum Hall plateaus at magnetic fields as low as 500mT.

The unique combination of physical properties found in graphene materials—one or few layers of carbon atoms on a honeycomb lattice—holds promise for future applications ranging from high frequency transistors ranging from high frequency on a honeycomb lattice—holds promise for future applications ranging from high frequency...
used in previous experiments can create structural defects which irreversibly affect the electronic properties of graphene. The suspension of the graphene samples is then accomplished by standard wet-etching of 150nm of SiO$_2$ in a solution of buffered HF (Fig. 1d and f).

Special care has to be taken during the final drying process of the sample since the surface tension of the liquids and the capillary forces can easily cause the collapse of the nano-structures. A common solution to this problem is to dry the samples in a critical point dryer (CPD) -making use of the zero surface tension in the supercritical transition of CO$_2$. However, after being dried in the CPD, the graphene surface is often covered by contaminants present in the liquids and/or the CO$_2$ gas used in the process. These contaminants dope the graphene, degrade its electrical properties such as the charge carrier mobility and they are also very difficult to anneal. Here we undertake an alternative route to dry the samples after etching, making use of the fact that both surface tension and capillary forces are temperature dependent -i.e. they decrease when approaching the boiling point of the liquids. Simply warming up the IPA at 50°C reduces significantly the surface tension of this liquid, making it possible to suspend the double-gated structures by just leaving them to dry in atmosphere. This procedure invariably delivers suspended double-gated graphene devices with flakes as large as 3µm wide and up to 2µm long. Fig. 2 shows a false colour SEM micrograph of a typical suspended and double gated graphene device taken under a shallow angle to highlight the multi-level structure comprising the air-gap top-gate and the suspended flake.

![SEM micrograph of a suspended and double gated graphene device](image)

**FIG. 2:** (a) False colour SEM micrograph of a suspended and double gated graphene device. (b) Resistance versus back-gate voltage ($V_{bg}$) before and after current annealing for a double gated trilayer graphene device.

We have characterized the electrical properties of these suspended and double-gated devices measuring the resistance with standard lock-in technique in a current- or voltage-biased configuration and in the linear regime - i.e. the excitation current (voltage) was varied to ensure that the voltage drop across the sample was smaller than the temperature broadening of the Fermi distribution. All the devices are current annealed in situ -i.e. in high vacuum ($10^{-6}$ mbar) and at low temperature $T = 4K$ with current densities as high as 1.4mA/µm$^2$. Upon annealing the residual doping of the samples is reduced to zero and the charge carrier mobility typically increases by at least one order of magnitude, see Fig. 2b. In total we have studied more than 5 double gated FLG devices, and in this letter we discuss the representative data of an ABC-stacked trilayer graphene.

![Resistance vs. back-gate voltage](image)

**FIG. 3:** (a) Resistance vs. back-gate voltage ($V_{bg}$) measured at $T = 0.3K$ and for different values of fixed top-gate voltage ($V_{tg}$) as indicated in the graph. (b) 2D-Raman peak measured with a 532nm laser, 5mW power and a spot size of 1.5 µm. The dots are the experimental data points, whereas the red continuous line is a fit to 6 Lorentzians (continuous blue lines). (c) Measurements of the on/off ratio of the current ($I_{on}/I_{off}$) as a function of the average electric displacement $D$.

![Conductance vs. back-gate voltage](image)

**FIG. 4:** Conductance vs. back-gate voltage measured at $V_{tg}=0V$ for different values of perpendicular magnetic field from 0.5T up to 1.9T in steps of 0.2T.

Both the stacking-order and the number of layers were reliably identified by means of Raman spectroscopy as previously reported$^{10,11,21,22}$. In particular the peak at 2700cm$^{-1}$ (2D-peak) in the Raman spectra of graphene depends on the band structure of the material. In trilayer graphene experimentally a minimum number of 6 Lorentzian functions can be used to describe the shape of the 2D peak, whereas the asymmetry of this peak (with a pronounced shoulder) identifies the rhombohedral stacking order (see Fig. 3b). Fig. 3b shows the 2-terminal resistance measured at $T=0.5K$ as a function of back-gate voltage ($V_{bg}$) for different fixed values of top-gate...
voltage \((V_{tg})\). It is apparent that the maximum of resistance increases with increasing the external perpendicular electric field. This observation is consistent with the opening of an electric field induced band gap in the energy dispersion of rhombohedral trilayer graphene\(^{2,11}\).

The high quality of these samples is demonstrated by the fact that we observe a particularly high on/off ratio of the current \((I_{on}/I_{off})\). If we define the average electric displacement as \(D = (D_{tg} + D_{bg})/2\) with \(D_{bg} = \frac{\varepsilon}{d+1}V_{bg}\) and \(D_{tg} = V_{tg}/d\) \((d = 150 \text{ nm}\) and \(\varepsilon = 3.9\) for \(\text{SiO}_2\)), we find that \(I_{on}/I_{off}\) equals 250 for \(D = -0.08V/nm\). The \(I_{on}/I_{off}\) value typically found in our devices is at least twice as large as previously reported in supported double gated bilayer graphene devices\(^{23}\).

Electrical transport measurements in perpendicular magnetic field reveal the formation of Landau levels (LLs) starting from \(0.5T\), with the appearance of magnetic field revealing the formation of Landau lev-

Experimentally we find that the unique quantization sequence of the rhombohedral trilayers \(G(e^2/h) = ±6, ±10, ±14, ±18...\) becomes clearly visible at magnetic fields as low as \(0.9T\). We identify the filling factors of the Quantum Hall plateaus at \(\nu = 6, 10, 14, 18\) with \(\nu = n_\phi B^{-1}\), where \(\phi_0\) is the flux quantum, \(n_\phi\) is the charge carrier density calculated using the known capacitance to the back gate and \(B\) is the magnetic field. The observed plateaus are expected from the 3-fold degenerate zero-energy LLs of the ABC-stacked trilayer graphene \((E_n \propto B^{3/2}\sqrt{n(n-1)(n-2)})\) with 4-fold spin and valley degeneracy\(^{21}\).

The high quality ABC-stacked trilayer devices invariably produced by this processing make it possible to access the quantum Hall physics at magnetic fields which are 2 orders of magnitude smaller than previously experimentally reported in supported double-gated devices\(^{26}\). S.R. and M.F.C. acknowledge financial support from EPSRC (Grant No. EP/G036101/1 and no. EP/J000396/1) and from the Royal Society Research Grant 2010/R2 (Grant no. SH-05052).

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