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Doping, Strain, Orientation and Disorder of Graphene by Raman Spectroscopy

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Raman spectroscopy is a fast and non-destructive method for the characterization of carbons [1]. These show two features: the G and D peaks, around 1580 and 1350 cm^{-1} respectively. The G peak corresponds to the doubly degenerate E_{2g} phonon at the Brillouin zone centre. The D peak is due to the breathing modes of sp^2 atoms and requires a defect for its activation [1-5]. It is common for as-prepared graphene not to have enough structural defects for the D peak to be seen [4,6], so that it can only be detected at the edges [6]. The most prominent feature in graphene is the second order 2D peak [6]. This is always seen, since no defects are required for its activation. Its shape distinguishes single and multi-layers [6]. Raman spectroscopy also monitors doping [7-9]. We report the evolution of the Raman spectra of single [7,8] and bi-layer [9] graphene as a function of doping. A Fermi level shift is induced either by applying a bottom gate [7], or by a polymeric top gate [8,9], or naturally happens as a result of charged impurities [10]. This induces a stiffening of the Raman G peak for both hole and electron doping [7]. This is explained including dynamic corrections to the adiabatic Born-Oppenheimer approximation [7]. The phonon renormalization of bilayer graphene has characteristic features compared to single layer. This allows a direct estimation of the interlayer coupling [7-9]. We then consider the effects strain. Uniaxial strain lifts the E_{2g} degeneracy and splits the G peak in two: G^+ and G^- . The peaks downshift as a function of strain allows a direct measurement of the Gruneisen parameter [10]. The polarization dependence of the G^+/G^- modes is a probe of the crystallographic orientation of the sample [10]. Finally, we consider the effect of disorder [3,4,11] and show how to discriminate between disorder, strain and doping [11]. We will also discuss how the D peak is a signature of π electron localisation, and, thus, of gap opening in chemically modified graphene[12].

1. A. C. Ferrari, J. Robertson (eds), *Raman spectroscopy in carbons: from nanotubes to diamond*, Theme Issue, Phil. Trans. Roy. Soc. **362**, 2267 (2004). 2. F. Tuinstra, J.L. Koenig, J. Chem. Phys. **53**, 1126(1970). 3. A. C. Ferrari, J. Robertson Phys Rev B **61**, 14095 (2000); **64**, 075414 (2001) 4. A. C. Ferrari Solid State Comm. **143**, 47 (2007) 5. S. Piscanec et al. Phys. Rev. Lett. **93**, 185503 (2004) 6. A. C. Ferrari et al. Phys. Rev. Lett. **97**, 187401 (2006) 7. S. Pisana et al. Nature Mater. **6**, 198 (2007) 8. A. Das et al, Nature Nano **3**, 210 (2008). 9. A. Das et al., arXiv:0807.1631v1 (2008) 10. A. C. Ferrari et al. submitted (2008) 11. C. Casiraghi et al. Appl. Phys Lett. **91**, 233108 (2007) 12. Elias et al. arXiv:0810.4706 (2008)