Graphene: recent advances on the growth and nanoscale electrical characterization

Filippo Giannazzo
e-mail: filippo.giannazzo@imm.cnr.it

Consiglio Nazionale delle Ricerche, Istituto per la Microelettronica e Microsistemi, Strada VIII, 5, 95121 Catania, Italy

Graphene [1,2], a two-dimensional (2D) layer of sp^2 hybridized carbon atoms arranged in a honeycomb lattice, is currently the object of large scientific interests, due to many unique electrical [3-5], magnetic [6], optical [7], thermal [8], and mechanical properties [9]. The most attractive ones are certainly the outstanding transport properties of the two-dimensional electron gas (2DEG). Giant carrier mobility (μ>10^5 $cm^2V^{-1}s^{-1}$) and micrometer electron mean free path (l) have been reported in graphene under proper experimental conditions, *i.e.* in suspended ultra-clean membranes [3] or in graphene encapsulated between inert and ultra-flat boron nitride layers [4, 5]. However, significantly lower values of l and μ are typically measured under practical conditions, *i.e.* in graphene devices on common substrates, at room temperature and under ambient environment. Literature values of mobility spread over a wide range, depending on the graphene synthesis method, on the substrate, but also on the processes used for graphene device fabrication. Typical values of μ, ranging from 10^3 to 10^4 $cm^2V^{-1}s^{-1}$, make graphene suitable for high frequency (GHz−THz) devices applications [10]. Furthermore, graphene can sustain current densities six orders of magnitude higher than copper without suffering of electromigration problems [11], making it useful for interconnects in electronics devices and/or integrated circuits. Finally, the high conductivity and high transparency (~97.7%) to light from visible to near-infrared wavelenghts [7], make graphene suitable as a transparent conductive electrode for photovoltaics or displays applications.

One major challenge towards graphene applications is the large area growth of laterally uniform films on suitable substrates. In this lecture, an overview of the main methods to obtain single of few layers of graphene will be provided [12]. In particular, the following approaches will be discussed: (i) exfoliation of graphite by mechanical or chemical (oxidative or not-oxidative) methods; (ii) epitaxial growth of graphene by thermal decomposition of hexagonal SiC; (iii) growth of graphene on catalytic metals (Ni, Cu) and transfer to different substrates (including flexible substrates). The advantages and disadvantages of the different methods, in terms of graphene crystallites sizes, electronic and structural quality, will be discussed also in relation to potential applications, ranging from RF devices to flexible electronics.

The electronic properties of the 2DEG in graphene will be discussed, starting from the peculiar energy band structure. A comparison with the properties of electrons in bulk semiconductors and of the 2DEG at semiconductor heterointerfaces will be performed. The various scattering mechanisms limiting graphene carrier mobility will be discussed deeply.

Being graphene a 2D layer totally exposed to the external environment, its electronic properties are strongly affected by structural or electrical inhomogeneities at the graphene/substrate interface or by adsorbed impurities/molecules. Since these inhomogeneities are inherently nanometric in size, high resolution electrical characterization methods are required to probe their effect on graphene electrical properties.

Some of the recent advances in scanning probe microscopy methods to measure graphene electronic properties with nanoscale resolution will be reported [12-21]. Scanning capacitance microscopy (SCM) has been employed to probe locally the lateral variations of the quantum capacitance and density of states in graphene [13]. A recently demonstrated method based on local capacitance measurements allowed to obtain two dimensional maps of the electron mean free path

in graphene with few-tens-nanometers lateral resolution [14]. The application of this methods allowed to clarify the role played by local scattering sources like charged impurities and defects (native or artificially introduced by ion irradiation) as limiting factors of graphene mean free path [14-17]. The impact of the substrate dielectric permittivity on the scattering by charged impurities will be discussed [14]. Conductive atomic force microscopy (CAFM) allowed to study the local current transport through epitaxial graphene/SiC interface [18] or in epitaxial graphene on SiC [19]. Recently, the joint application of nanoscale conductivity measurements in epitaxial graphene by CAFM and atomic resolution structural analyses of epitaxial graphene/SiC interface by scanning transmission electron microscopy (STEM) allowed to clarify some peculiar properties of electronic transport in epitaxial graphene layers [20]. Recently, CAFM was also applied allowed to study the electrical properties of graphene grown by CVD on copper and transferred to plastics substrates [21].

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