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Review article

The role of contact resistance in graphene field-effect devices

Filippo Giubileo [a,*], Antonio Di Bartolomeo [a,b]

[a] CNR-SPIN Salerno, via Giovanni Paolo II 132, Fisciano (SA), Italy
[b] Physics Department, University of Salerno, via Giovanni Paolo II 132, Fisciano (SA), Italy

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ABSTRACT

The extremely high carrier mobility and the unique band structure, make graphene very useful for field-effect transistor applications. According to several works, the primary limitation to graphene based transistor performance is not related to the material quality, but to extrinsic factors that affect the electronic transport properties. One of the most important parasitic element is the contact resistance appearing between graphene and the metal electrodes functioning as the source and the drain. Ohmic contacts to graphene, with low contact resistances, are necessary for injection and extraction of majority charge carriers to prevent transistor parameter fluctuations caused by variations of the contact resistance. The International Technology Roadmap for Semiconductors, toward integration and down-scaling of graphene electronic devices, identifies as a challenge the development of a CMOS compatible process that enables reproducible formation of low contact resistance. However, the contact resistance is still not well understood despite it is a crucial barrier towards further improvements. In this paper, we review the experimental and theoretical activity that in the last decade has been focusing on the reduction of the contact resistance in graphene transistors. We will summarize the specific properties of graphene-metal contacts with particular attention to the nature of metals, impact of fabrication process, Fermi level pinning, interface modifications induced through surface processes, charge transport mechanism, and edge contact formation.

Contents

* Corresponding author.
E-mail address: filippo.giubileo@spin.cnr.it (F. Giubileo).

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1. Introduction

Graphene is a two-dimensional material composed of an atomically thick layer of sp^2-bonded carbon atoms arranged in a honeycomb structure, in which three covalent bonds are formed in the plane by the hybridization of the 2*s* orbital with the $2p_x$ and $2p_y$ orbitals with the characteristic angle of 120°. The orbital p_z is perpendicular to the plane and forms a weak π-bond. The weakness of the Van-der-Waals force between layers in the three-dimensional graphite causes the easy peel-off of single graphene sheets from the bulk material. Indeed, the single layer graphene was obtained in 2004 by mechanical exfoliation of highly oriented pyrolytic graphite, repeatedly peeling flakes by scotch tape [1]. The π-bonds are not localized and are responsible for electronic conduction properties in the graphitic structures. Graphene has been known for many years as the building block of graphite, and its electronic band structure was first calculated already in 1947 [2] within the nearest-neighbor tight-binding theory. The conduction and the valence bands are not separated by a gap, and they meet in two inequivalent points, called Dirac points, of the Brillouin zone. The Fermi level for undoped graphene lies exactly at the Dirac points, and graphene can be considered a gapless semiconductor or a zero-overlap semimetal. The electron dispersion $E(k)$ around the Dirac points is linear rather than parabolic, as in most semiconductors. The charge carriers behave as relativistic massless particles moving with an effective speed $v \approx 10^6$ m/s. Consequently, the electron transport properties are described by the Dirac's equation, with several (relativistic) quantum mechanical effects [3–7] such as the unusual half-integer quantum Hall effect [4], Klein tunneling effect [7], minimum conductivity [5], and Veselago lensing [8].

Along with its unique electronic properties, graphene has shown several interesting properties:

i) The optical absorption of single layer graphene is $A \approx 1 - T \approx \pi\alpha \approx 2.3\%$ (i.e., $T \approx 0.977$, where $\alpha = e^2/(4\pi\varepsilon_0\hbar c) \approx 1/137$ is the fine-structure constant) [9], to be compared with the maximum visible transmittance of $T \approx 0.81$ for indium tin oxide that represents the state of the art transparent conductor. Moreover, graphene only reflects <0.1% of the incident light in the visible region;
ii) The mechanical breaking strength of defect-free single layer graphene, probed by nanoindentation in atomic force microscopy, is 42 N/m corresponding to an extraordinary Young's module of ∼1 TPa [10] and intrinsic strength of ∼ 130 GPa, confirming the graphene as the strongest material;
iii) The intrinsic thermal conductivity K has been experimentally obtained for suspended graphene by optothermal Raman technique reporting $K \sim 5 \cdot 10^3$ $Wm^{-1}K^{-1}$ at room temperature [11]. For few layer graphene K values decrease with the number of layers [12] approaching the graphite limit of ∼2000 $Wm^{-1}K^{-1}$. The thermal properties also include the unique characteristic of a negative thermal-expansion coefficient $\alpha = -4.8 \cdot 10^{-6}$ K^{-1} with a sign change at $T \approx 900$ K for single layer graphene and $T \approx 400$ K for bilayer graphene [13], as well as a very high melting point that has been estimated by atomistic Monte Carlo simulations as $T_m \simeq 4510$ K [14].

Graphene extraordinary properties have been already exploited for several applications such as gas sensors [15], photodetectors [16,17], solar cells [18], heterojunctions [19], field-effect transistors [20,21], transparent conductors for touch screens [22,23], electromagnetic interference shielding [24], interconnects [25], flexible electronics [26], nanoelectromechanical systems [27], and antennas [28].

The electrical properties of graphene make it one of the most promising candidate for next-generation high-speed field-effect transistors. However, the contact resistance of metal/graphene interface represents a crucial limiting factor for the device's performance, affecting for instance the transconductance, the *ON/OFF* current ratio and the *cut-off* frequency.

Several studies concerning the contact resistance have reported large sample-to-sample variations. Indeed, contact resistance depends on several factors such as type of metal, substrate, self-doping, fabrication process, contact geometry. Moreover, discrepancies can be likely due also to measurement methods and/or conditions.

In this review, we first summarize the graphene properties, such as electronic band structure, carrier mobility and band gap engineering, particularly relevant for the development of high performance field effect transistors and more generally electronic devices. After that, we discuss the physics of the metal/graphene interface, the arising contact resistance and the most used measurement methods. Finally, we review the experimental and theoretical activity for improving the contact resistance via surface treatments, work function engineering, contact design, etc.

2. Graphene properties for field effect transistor applications

The Moore's law has correctly predicted for decades that about 18–24 months are necessary to double the number of transistors packed into an integrated chip and it has represented a continuous reference for the semiconductor industry