Graphene field effect transistors for bioelectronic applications

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The development of the future generation of neuroprosthetic devices will require the advancement of novel solid-state sensors with a further improvement in the signal detection capability, a superior stability in biological environments, and a more suitable compatibility with living tissue. Due to the maturity of Si technology, Si-based MOSFETs have been extensively used in previous decades for these applications. However, several disadvantages of Si technology, such as a relatively high electronic noise and poor stability in aqueous environment have motivated the search for more suitable materials. In this respect, the outstanding electronic and electrochemical performance of graphene holds great potential for bioelectronic applications.

In this contribution, we will discuss our work towards the development of a graphene-based platform for applications in bioelectronics. In particular, we will report on graphene solution-gated field effect transistors (G-SGFETs) which can detect the electrical activity of electrogenic cells. Arrays of SGFETs were fabricated using CVD-grown graphene, grown on Cu and transferred to insulating substrates. Typically, 4x4 transistor arrays with dimensions of the device's active area of 20x10 μm^2 were processed and encapsulated for in-electrolyte characterization (Fig 1a). The electronic properties of these devices were investigated by Hall effect experiments performed under electrolyte-gate controlled conditions. The obtained mobility-carrier density curves (Fig 1b) are typical for high quality CVD graphene, with a carrier mobility limited by surface polar phonon scattering introduced by the polar sapphire substrate. The carrier mobility reaches values up to 10^4 cm^2/Vs, in the low carrier density regime.

Graphene SGFETs (Fig 1c) are compared to state-of-the-art Si-SGFETs based on the sensitivity and low-frequency noise performance of these devices [1]. The high carrier mobility in graphene, together with the large interfacial capacitance at the graphene/electrolyte interface, leads to transconductive sensitivities one order of magnitude higher than for Si devices [2]. Furthermore, G-SGFETs exhibit very low electronic noise, with an RMS value that is equivalent to gate signals of less than 8 µV [3].

The biocompatibility of CVD graphene has been study using cultures of pure retinal ganglion cells (RGCs). Our results confirm that graphene exhibit similar behavior than other biocompatible materials such as glass. In addition, it will be shown how the growth of RGCs neurites can be directed by graphene patterning. Further, we will report on the recording of the electrical activity of different cell lines using arrays of graphene solution-gated field effect transistors (Fig 2a). Action potentials induced in dense cultures of cardiomyocytes-like HL-1 cells are spatially and time-resolved by the graphene SGFETs (Fig 2b) [3]. The electrical coupling between a single cell and a graphene SGFET was studied by using HEK cells in a patch-clamp configuration. Without the need of signal averaging, single recordings reveal not only the electrical but also the chemical activity at the cell/transistor interface (Fig 2c). These results demonstrate the potential of graphene to outperform state-of-the-art Si-based devices for biosensor and bioelectronic applications.

Finally, we will discuss how the facile integration of graphene with flexible substrates, together with the excellent signal-to-noise ratio of graphene FETs and their sensitivity to the electrolyte composition hold great potential in the field of electrically functional neural prostheses [4].

Acknowledgments

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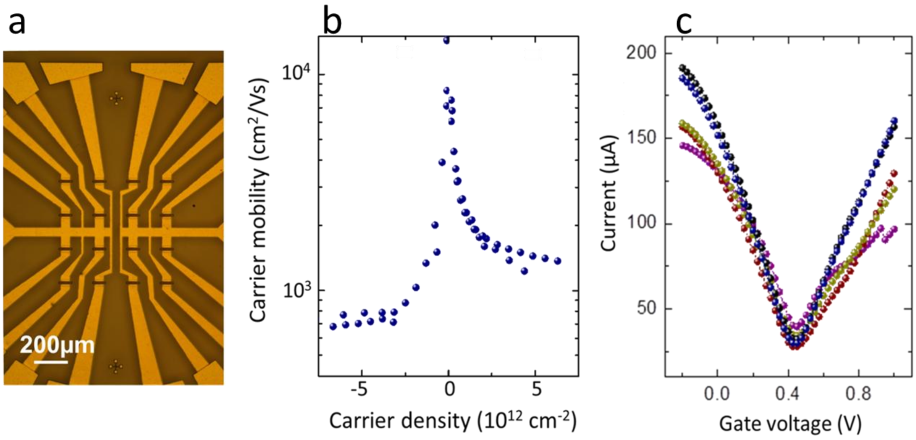
References

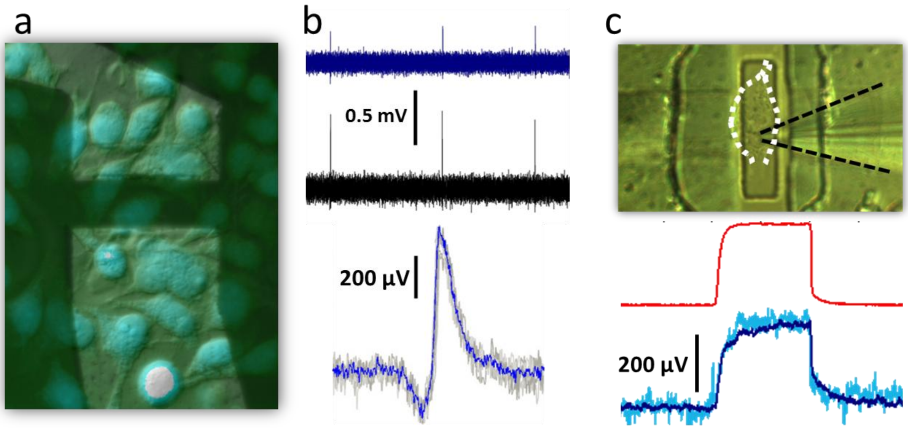
[1] Danker et al., Adv. Funct. Mater., **20** (2010) 3117
[2] Hess et al., Appl. Phys. Lett., **99** (2011) 033503
[3] Hess et al., Adv. Mater., **23** (2011) 5045
[4] Work in progress under the FP7-EU project NEUROCARE

Figure 1



a. Graphene transistor array on sapphire. b. Hall-effect carrier mobility versus carrier density for CVD grown graphene structures measured using an electrolyte gate. c. Typical transistor curves measured in electrolyte with a Ag/AgCl reference electrode. Transistor dimensions are 20x10 µm^2.

Figure 2



a. Human embryonic kidney (HEK) cells cultured on a graphene transistor. b. Recordings of the transistor array in a culture of cardiomyocyte-like cells, revealing the spontaneously elicited action potentials and noise levels below 30 µV. c. HEK cell on a transistor gate region stimulated with a pipette electrode. The transistor recording (light blue=single recording, dark blue=averaged signal) nicely follows the stimulation current signal (red curve).