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Graphene Solution-gated FET-based Electrocardiography Sensor

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Abstract

The field of bioelectronics has always fascinated the scientific community. Our curiosity about the mechanisms by which electrically excitable cells sense, process and respond to electrical stimuli has philosophical roots, as it ultimately aims to understand the main control systems of ourselves. More pragmatically, the study of electrical bio-signals allows to measure, identify, and recognize patterns that can be indicative of the health status of living organisms. Among the available electrical tests that are clinically relevant, electrocardiography is the most common electrophysiological assessment of human cardiac function, both in terms of structure and electrical activity, as reported by Tison et al. [1] in 2019. Conventionally, electrocardiograms (ECGs) are obtained using electrodes, generally consisting of silver/silver-chloride (Ag/AgCl), which transduce ionic currents in a patient's body to electric currents in an acquisition instrument. [2] In addition, wireless ECGs recorded with capacitive electrodes, which do not require a conductive contact between the patient and the acquisition instrument, have also been shown by Lim et al. [3] in 2006. Hence, ECG sensors based on the measurement of changes in electric currents or electric fields associated to cardiac cycles have already been demonstrated. Despite the maturity of ECG recording techniques, dating to the end of the 19th century, a novel recording strategy has emerged in the literature over the last decade. More specifically, solution-gated field-effect-transistors (SG-FETs) have been exploited in to record cardiac activity [4, 5, 6, 7]. In this context, one of the main advantages of using FET-sensors over ordinary Faradaic electrodes, may be increased signal-to-noise-ratio (SNR) of the recordings. One example of FET-based ECG sensors was reported in 2014 by Campana et al. [4]. They demonstrated an organic-electrochemical-transistor (OECT) showing a signal-to noise ratio (SNR) that was comparable to ECG Faradaic electrodes. With a channel of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), their OECT was flexible, conformable to human skin and transparent. In June 2020, Cea et al. [5] reported an ion-gated OECT (IG-OECT) that demonstrated a superior SNR value than the one of commercially available electrodes (3M Red Dot) when tested for ECGs: 54 dB and 37 dB, respectively. Their device consisted of a PEDOT:PSS - poly(ethylene imine) transistor channel gated via a chitosan ion membrane. The same year, in July 2020, Jo et al. [6] reported a biocompatible and biodegradable electrolyte-gated-transistor (EGT) for ECGs with superior signal to noise ration than conventional electrodes. The device had an organic channel of carboxyl-functionalised poly(3-hexylthiophene), poly[3-(5-carboxypentyl) thiophene-2,5-diyl] (P3CPT) gated via a solid-state electrolyte composed of levan polysaccharide.

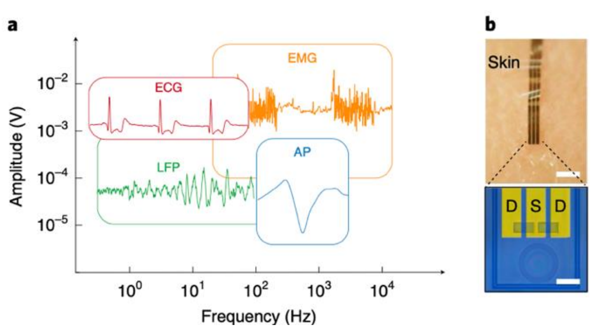

Figure 1: Results reported by Cea et al. in June 2020. (a) Amplitude and frequency characteristics of in-vivo electrical signals. (b) Image of an IG OECT device on human skin (top scale bar = 150 µm, bottom scale bar = 100 µm). Figure and caption adapted from [5].

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In 2017, Ameri et al. [8] presented graphene tattoo electrode sensors for ECG recordings and SG-FETs have been already demonstrated for the same application with different channel materials. Hence, this paper presents the novel idea of designing, developing, and testing the prototypes of SG-FETs for ECG recordings with graphene channels. As a bidimensional layer of carbon atoms, graphene was first isolated by Geim and Novoselov in 2004 [9]. The material properties include a breaking strength of 42 $N\ m^{-1}$ [10], an electrical mobility higher than 6000 $cm^2\ V^{-1}\ s^{-1}$ at room temperature [11], and high surface to volume ratio. These features allow to develop novel FET-sensors for ECGs with increased wearability, durability, and high SNR. Additionally, the readout electronics for SG-FET-based devices differs from conventional bio-signal amplifiers adopted in existing ECG monitoring instrumentation, paving the way towards a new class of front-end electronics suitable to operate in noisy environments, as required for instance to detect hidden clinically relevant features from ECG smart patch devices with a reduced number of electrodes operating in noisy environments.
This contribution will present the design and latest results of a first-in-class graphene-based SG-FET ECG sensor prototype and comparative analysis with conventional Ag/AgCl-based gel electrodes. Data collected with the novel ECG sensor will be analysed to determine their suitability to reveal clinically relevant features from wearable devices embedding the proposed sensor architecture in both healthy individuals and patients affected by cardiac-related morbidities, such as arrythmias.

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1. **Author contributions:**

GM conceived this work, wrote this paper and develops the experimental phases. TRK contributes to the fabrication and testing of the graphene SGFET ECG sensor. LGO supervises and coordinate the project.