Solution-based graphene for high-performance flexible electronics

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Abstract

The potential of graphene transistors for radio-frequency (RF) electronics was recently demonstrated by several groups using exfoliated, SiC-based and CVD-based graphene. The most recent studies reached de-embedded current gain cut-off frequencies (f_T) in the 100-300 GHz range with room for improvement at both the material and device levels. In parallel, graphene is being explored for large scale electronics on flexible substrates via CVD growth on metal foils associated with transfer methods. This progress is notably driven by the perspective of replacing ITO as the material of choice for the transparent electrodes required in applications such as touch screens, flat panel displays or organic photovoltaic cells. However, the combination of these two properties, namely high speed and flexibility, remains an open challenge. In particular for the viable development of fast and flexible electronic applications in the areas of portable / wearable communicating devices with low power consumption, this combination should be achieved with a source of material adapted to large-scale exploitation. Progress in the field notably implies to *(i)* build and characterize RF flexible devices, and *(ii)* to develop low-cost methods for the controlled production of large scale and high quality 2D materials thin films.

Concerning the first point, printed electronics based on organic materials is a well-established field. Organic materials are particularly well suited for flexible circuits due to their mechanical resiliency. Yet, their low charge mobility limits their ultimate operating frequency. While several examples of organic devices and circuits operating in the kHz to MHz range have been demonstrated, these approaches fall well short of the GHz range. Graphene transistors on flexible substrates were realized by several groups, but up to now, their high frequency performances were not evaluated. We recently demonstrated [1] that solution-based single-layer graphene ideally combines the required properties and presents important advantages over alternative graphene sources. For this study, we employed solution-based, predominantly single-layer graphene flakes isolated via density gradient ultracentrifugation [2]. The devices (see Figure 1) operate at low bias (V_{DS}<0.7 V), achieve current gain cut-off frequencies f_T as high as 2.2 GHz before de-embedding (8.7 GHz after de-embedding), power gain cut-off frequency f_{MAX} of 550 MHz and have a constant transconductance in the GHz range [1]. RF measurements directly performed on bent samples show the remarkable mechanical stability of these devices and demonstrate the advantages of solution-based graphene FETs over organic materials for analog RF electronics.

Concerning the second challenge, the CEA developed an original method for the controlled formation of highly-order thin films of nano-objects (including nanowires, carbon nanotubes and graphene oxide flake) based on the transfer of surfactant-stabilized water films [3,4]. We modified and optimized this method [5] to allow the homogeneous and large-scale assembly of very large graphene oxide flakes onto all type of substrates including organic flexible ones. The film thickness can be very precisely controlled from individual flakes to multi-layers (see Figure 2). The films show remarkably low roughness and the flakes are almost totally wrinkles-free. After reduction, the reduced graphene oxide (rGO) films reach transparencies and conductivities compatible with their integration into prototype photovoltaic cells. We notably used Time Resolved Microwave Conductivity (TRMC) and graphene/silicon solar cells to study the mechanism of charge separation at the carbon/silicon interface.

References

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Figures

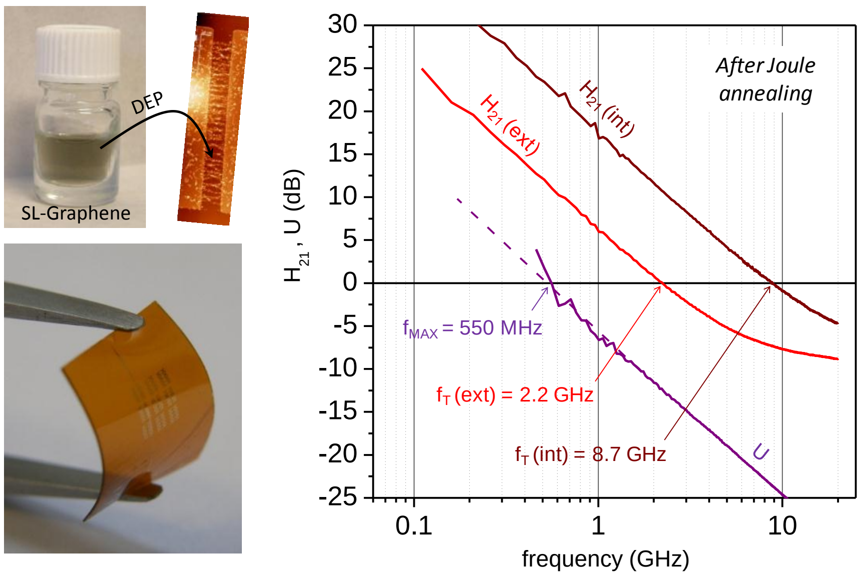

Figure 1 : Solution-based single-layer graphene flakes assemble by dielectrophoresis (DEP) on a polyimide substrate and integrated into high-frequency top-gated FET device structures. Evolution of the current gain H_{21} (before and after de-embedding) and of the power gain U of such flexible FET after Joule annealing. The de-embedded cut-off frequency f_T is 8.7 GHz.

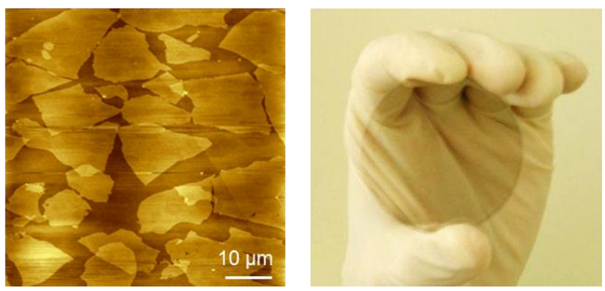

Figure 2 : (left) AFM image of a sub-monolayer assembly of large and *wrinkle-free* graphene oxide flakes. (right) Two-inch quartz wafer covered with an ultra-smooth reduced graphene oxide multi-layer film forming a conductive and transparent electrode.