Flexible GHz Transistors Derived from Solution-Based Single-Layer Graphene

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The potential of graphene transistors for high frequency 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 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 low-cost manufacturing methods such as ink-jet printing.

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. Conversely, inorganic semiconducting materials such as III-V semiconductor nanowires and silicon thin films can reach the GHz range, but few studies have evaluated their performances upon severe bending and these inorganic materials are not ideally adapted for future printed technologies. Carbon-based nanomaterials potentially combine high speed performance with the required mechanical properties. In particular, carbon nanotubes were used to develop high frequency transistors on rigid substrates and to demonstrate flexible devices and circuits. Recently, graphene transistors on flexible substrates were realized, but their high frequency performance was not evaluated.

In this work [1], we demonstrate that solution-based single-layer graphene ideally combines the required properties and presents important advantages over alternative graphene sources that are chemically grown or mechanically exfoliated. Several methods of producing stable graphene-based suspensions have been recently demonstrated. In particular, there have been extensive efforts to utilize graphene oxide as a solution-phase precursor for graphene. However, this approach requires subsequent chemical reduction treatments that preclude complete recovery of the superior electrical properties of pristine graphene. Alternatively, exfoliation of graphite is also possible. While this procedure is effective at isolating few-layer pristine graphene, polydispersity in the thickness of graphene produced from these processes implies inferior performance compared to single-layer graphene in high-performance electronic applications. To overcome these issues, we employ solution-based, predominantly single-layer graphene flakes isolated via density gradient ultracentrifugation [2] to fabricate flexible transistors on organic substrates operating at GHz frequencies. The devices 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]. In addition, we show that both the electron and hole conduction branches display high-speed performance, in contrast with previous reports where only one type of carrier was considered due to the either high n-type or p-type doping of the graphene used. 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 other types of flexible transistors based on organic materials.

References

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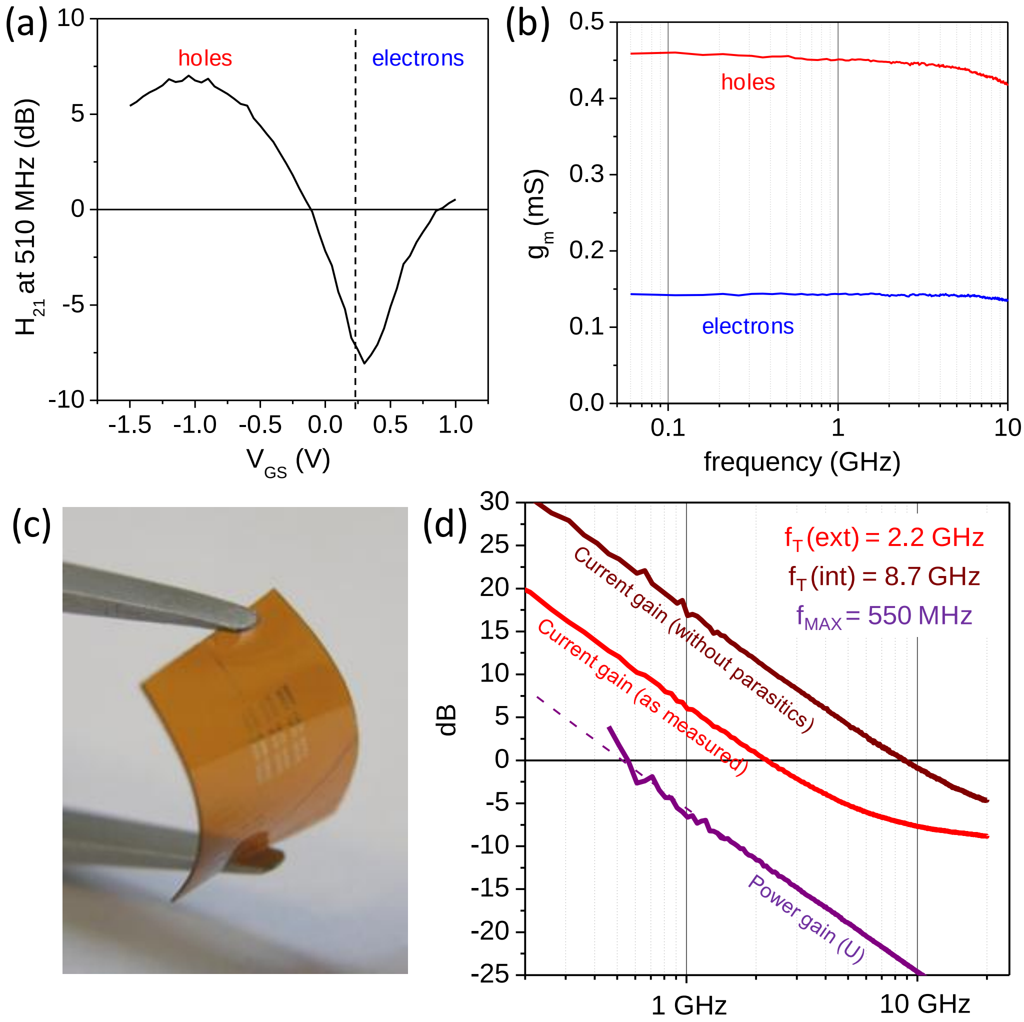

(a) Evolution of the current gain H_{21} measured at 510 MHz as a function of the gate bias of an as-prepared graphene-FET on polyimide. (b) Evolution of the transconductance as a function of frequency showing stable performances up to ~5 GHz (V_{GS}=-1V for holes and 1V for electrons). (c) Picture of a series of flexible graphene FETs on polyimide. (d) Evolution of the current gain H_{21} (before and after de-embedding) and of the power gain U for a p-type device after Joule annealing. The as-measured cut-off frequency f_T is 2.2 GHz.