Integrated graphene high-gain voltage amplifiers and ring oscillators

Marco Fiocco,[1] Erica Guerriero,[1] Abhay A. Sagade, [2] Daniel Neumaier,[2] Roman Sordan[1]

[1]L-NESS, Department of Physics, Politecnico di Milano, Via Anzani 42, 22100 Como, Italy
[2]AMO GmbH, Otto-Blumenthal-Strasse 25, 52074 Aachen, Germany
roman.sordan@polimi.it

Graphene has been investigated as a possible contender in high-frequency electronics due to its high charge carrier mobility, which is larger than that of conventional high-mobility semiconductors, such as InP or SiGe. However, the applications of graphene in commercial electronics are virtually non-existent, as only laboratory prototypes have been demonstrated so far. This apparent discrepancy occurs because of a very low voltage gain A_v exhibited by typical graphene electronic devices and by large device to device variations. Without $|A_v| > 1$ and reproducible device characteristics it is not possible to realize more complex (i.e., realistic) electronic circuits relying on the amplification of signals and on cascading of different stages. As a consequence, early graphene electronics was entirely based on proof-of-principle operation of single-transistor and single-stage circuits. Such circuits are unusable in real applications in which a large number of transistors and stages are required to obtain the required functionality.

The main reason for a low voltage gain in graphene electronic devices is the absence of a bandgap in graphene. This prevents the depletion of charge carriers in graphene field effect transistors (GFETs) and therefore increases the output conductance g_d due to the absence of drain current saturation. In order to increase the intrinsic gain $A = g_m/g_d$ of GFETs and consequently the voltage gain A_v in graphene circuits, it is necessary to maximize the transconductance g_m of GFETs. To this end very thin high-k gate oxides, high-quality graphene materials, and metal contacts exhibiting a low contact resistance have been implemented in GFETs. In this way, $|A_v|$ in the range of 1.7 to 7 has been demonstrated both in exfoliated [1-3] and large-scale graphene samples [4-8]. However, there have been no previous demonstrations of $|A_v| > 10$ (i.e., > 20 dB) in monolayer graphene electronic circuits, which would represent an important milestone of achieving a signal amplification of an order of magnitude. Here we demonstrate the first voltage amplifiers integrated on a large-scale monolayer graphene exhibiting $|A_v| > 10$. Graphene ring oscillators (ROs), circuits often used as a test-bench for new technologies, have been realized using such inverters with submicron gate lengths, proving the reproducibility of device characteristics. The oscillation frequency was 1.8 GHz, which is the highest oscillation frequency reported to date in an oscillator made of any low-dimensional material.

Graphene amplifiers were realized in a complementary configuration (Fig. 1). Equivalent oxide thickness (EOT) of only ~ 2 nm was obtained by direct evaporation of Al on graphene, which upon exposure to air naturally forms a very thin AlO_x insulator at the interface with graphene. High mobility of graphene samples grown by chemical vapor deposition was preserved by careful transfer from Cu foils to float-zone Si substrates (resistivity 5 kΩcm) with 1 µm thick SiO_2 on top. Low contact resistance was obtained by contacting the graphene with purely Au contacts, without the use of any adhesion layers. Low EOT and contact resistance together with the high mobility of the graphene resulted in high voltage gain of the fabricated inverters obtained already at low voltage supplies ($V_{DD} < 2$ V), as evidenced by their DC characteristics (Fig. 2). High voltage gain of $A_v \sim -11$ was directly measured in the AC regime (Fig. 3), demonstrating highly stable device characteristics of the fabricated devices.

Graphene ROs were realized by cascading three graphene inverters in a loop, with the fourth inverter decoupling the RO from the measurement equipment connected to the output (Fig. 1). High voltage gain and very small Dirac voltages in the fabricated inverters allowed in/out signal matching and induced oscillations at high frequencies (Fig. 4). The highest oscillation frequency was 1.8 GHz and it was obtained in ROs with the gate length of 800 nm, demonstrating intrinsic voltage gain $A > 1$ in submicron GFETs. Demonstrated graphene electronic circuits are an important step toward the application of graphene in electronics.

This research was supported by Fondazione Cariplo (grant no. 2011-0373), PRIN project GRAF, and Graphene Flagship (grant no. 604391).

References

[1] A. Sagar et al, Appl. Phys. Lett., **99** (2011) 043307.
[2] E. Guerriero et al., Small, **8** (2012) 357.

[3] B. N. Szafranek et al., Nano Lett., **12** (2012) 1324.
[4] S.-J. Han et al., Nano Lett., **11** (2011), 3690.
[5] L. G. Rizzi et al., Nano Lett., **12** (2012) 3948.
[6] Y. Wu et al., Nano Lett., **12** (2012) 3062.
[7] E. Guerriero et al., ACS Nano, **7** (2013) 5588.
[8] D. Schall et al., Sci. Rep., **3** (2013) 2592.

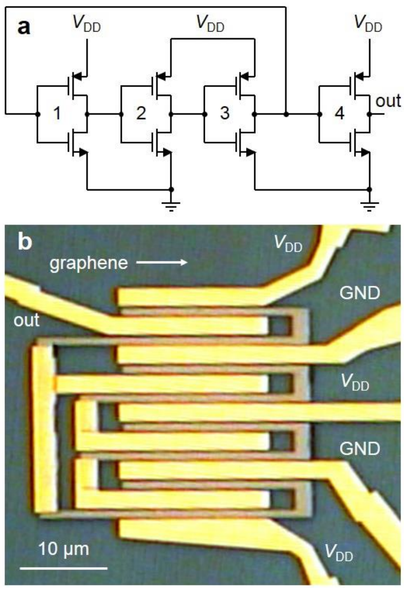

Figure 1 Integrated monolayer graphene voltage amplifiers and ROs. a) Circuit diagram of a three-stage RO with a fourth stage acting as a buffer. Single inverting stages were separately investigated as voltage amplifiers. b) An optical image of a graphene RO with the gate length of 800 nm.

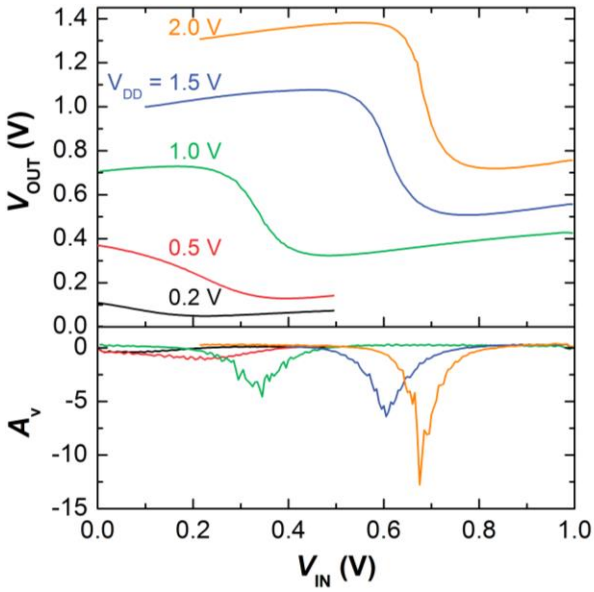

Figure 2 DC transfer curves and voltage gain A_v of one of the fabricated graphene inverters at different supply voltages V_{DD} under ambient conditions.

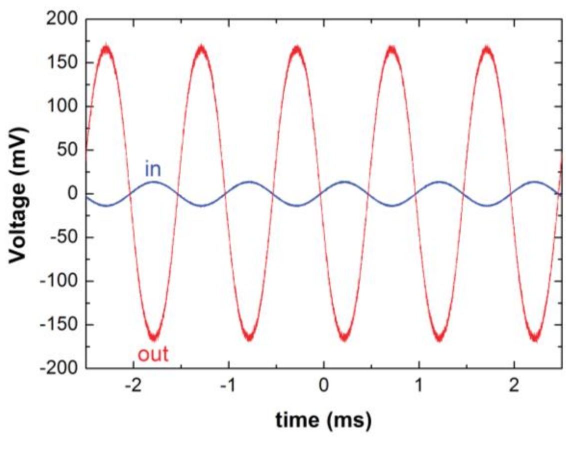

Figure 3 AC components of the input and output voltage signals measured in a graphene inverter in ambient air at a frequency f = 1 kHz for V_{DD} = 3 V. The voltage gain is $A_v = -11.3$.

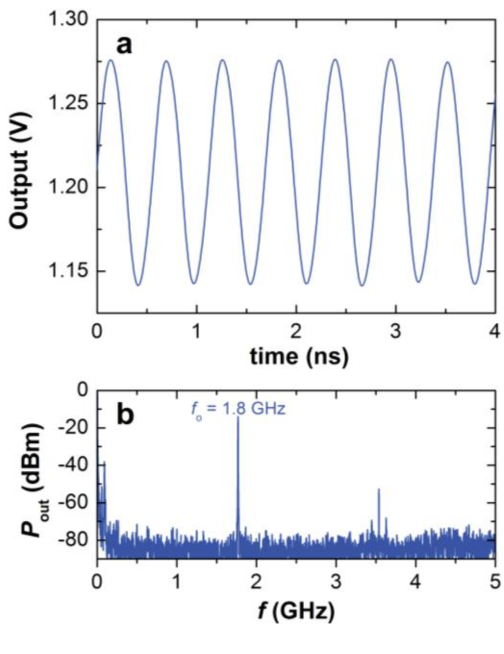

Figure 4 Output signal of one of the fabricated graphene ROs at V_{DD} = 1.9 V. a) Waveform. b) Power spectrum.