Graphene audio voltage amplifier

Roman Sordan, Erica Guerriero, Laura Giorgia Rizzi, Massimiliano Bianchi, Laura Polloni

Department of Physics, Politecnico di Milano, Polo di Como, Via Anzani 42, 22100 Como, Italy
roman.sordan@como.polimi.it

The main building block of analog electronics is a voltage amplifier: an electronic device capable of amplifying small alternating current (AC) voltage signals. Many graphene analog electronic devices, performing different functions,[1-5] have recently been proposed stemming from high carrier mobility[6,7] and ambipolar transport in graphene field effect transistors (FETs). However, none of these devices was capable of signal amplification, thus ultimately requiring integration with Si transistors for performing this most important task. Here we demonstrate an integrated graphene voltage amplifier paving the way for all graphene analog electronics.[8]

Signal amplification was obtained by fabricating graphene transistors in which the top Al/Al_2O_3 gate stack overlaps with the Ti/Au source and drain contacts (Figure 1a,b). A similar full-channel coverage exists in conventional Si metal-oxide-semiconductor FETs and allows maximum drain current modulation as there are no ungated parts of the channel that contribute to fixed series resistances which reduce the voltage gain. The Al_2O_3 layer which forms on the surface of the Al gate prevents short circuits between the contacts. The gate also serves as an additional heat sink which allows high drain currents I_D and consequently high voltage gain A_v. Additionally, as the gate fully covers the channel, desorption of adsorbates from graphene is suppressed at high drain currents, and therefore the electrical properties of FETs are stable during operation. Voltage amplifiers were realized in a complementary push-pull configuration (Figure 1c).

Figure 2a shows measured AC components of the input and output voltage signals of the amplifier biased at $V_{DD} = 2.5$ V. At this supply voltage a maximum voltage gain $|A_v|_{max} = 3.7$ (11.4 dB) was measured at an input frequency f of 10 kHz. The frequency response of the fabricated amplifier in the frequency range $f < 5$ MHz is shown in Figure 2b. High gain is preserved at very low frequencies due to a direct coupling both at the input and output of the amplifier (i.e., there is no lower cut-off frequency). The gain remains constant up to about 20 kHz, and then decreases as the frequency is increased, dropping by 3 dB at the higher cut-off frequency $f_{-3\,dB} = 70$ kHz which also defines the bandwidth of the amplifier. The amplifier is capable of signal amplification up to a unity-gain frequency $f_1 = 360$ kHz. At this frequency, the amplifier operates as a unity-gain amplifier (buffer), while for $f > f_1$ it attenuates the input signal. The signal phase shift φ introduced by the amplifier is 180° at low frequencies (signal inversion), decreasing to 90° at high frequencies. Both amplitude and phase characteristics of the voltage gain indicate a typical dominant-pole (at $f_{-3\,dB}$) behavior. However, this pole does not originate from the amplifier but from the capacitances of the cables used to connect the amplifier to the measurement equipment (an intrinsic unity-gain frequency can be estimated to be ~ 9 GHz).

Even higher gains could be obtained with higher supply voltages, with the use of gate dielectrics with higher breakdown voltages. The obtained values demonstrate that, among other applications, the present graphene amplifier is suitable for high fidelity amplification of audio signals. The high voltage gain obtained in our devices can also be utilized to fabricate graphene digital logic gates which can be directly coupled.

References

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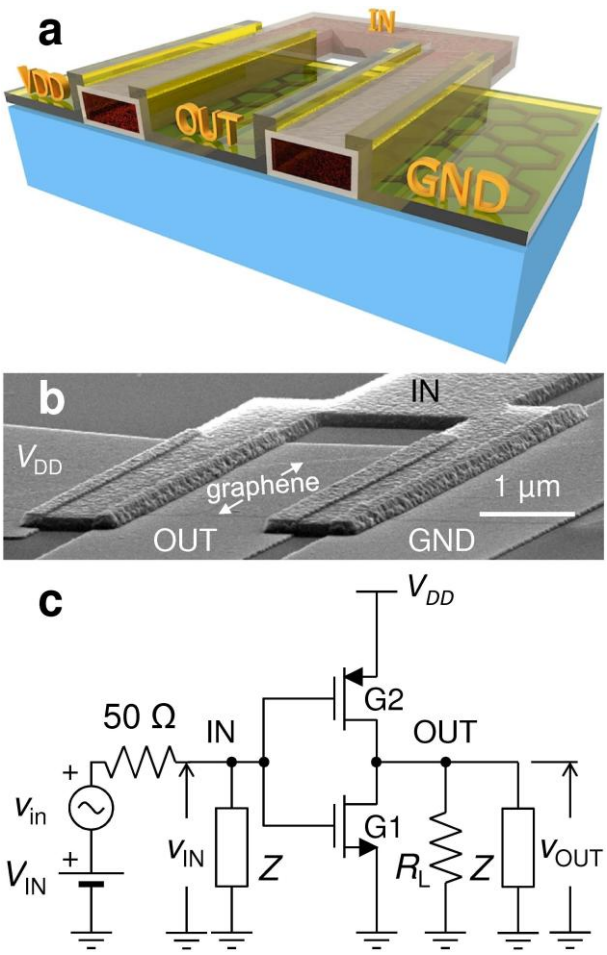

Figure 1 *Integrated graphene voltage amplifier. a) A schematic of an amplifier. Source (VDD, GND) and drain (OUT) contacts (Ti/Au) overlap with gate (IN) contacts (Al; dark core) covered by an insulating layer (Al_2O_3; bright shell). b) A tilted scanning electron microscope image of a device. The arrows indicate the extent of the graphene flake. c) A circuit diagram of the amplifier. Z = 1 MΩ || 13 pF is the input impedance of the oscilloscope used to measure input and output signals while 50 Ω is the output resistance of the input voltage source. Since |Z| >> 50 Ω the input signal fully drops across Z, i.e., $v_{IN}(t) = V_{IN}+v_{in}(t)$, where V_{IN} is the DC bias voltage and $v_{in}(t)$ is the AC component of the input signal. The amplifier is additionally loaded with R_L which simulates the input resistance of the next amplifying stage. This resistance was either infinite, 30 kΩ, or 10 kΩ, depending on the measurement.*

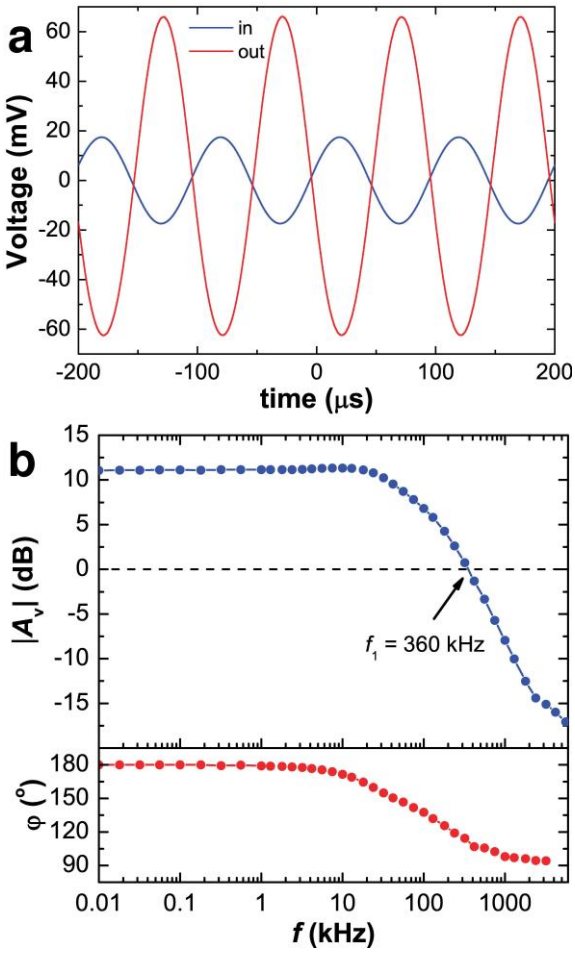

Figure 2 *Voltage amplification. a) AC components of the input and output voltage signals at a frequency f = 10 kHz for V_{DD} = 2.5 V and $R_L \to \infty$. The voltage gain is $A_v = -3.7$. The DC components of the signals are V_{IN} = 0.15 V and V_{OUT} = 1.15 V. b) Frequency response $A_v = |A_v|\angle\varphi$ of the amplifier for V_{DD} = 2.5 V and $R_L \to \infty$. Top: Magnitude $|A_v(f)|$ of the voltage gain. The magnitude decreases at 18 dB/dec at high frequencies, which is very close to the decrease of 20 dB/dec expected from a dominant pole at $f_{-3\,dB}$. Bottom: Phase shift φ(f) between output and input signals introduced by the amplifier.*