Compact modeling of external parasitics of graphene field-effect transistors

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Abstract

Graphene is a promising candidate for future high-performance RF applications [1]. Its potential to substitute conventional silicon technology has been demonstrated with devices such as a graphene field-effect transistor (GFET) with an intrinsic cut-off frequency of 427 GHz [2]. Recently, research on graphene-based RF electronics has been extended to the circuit level and basic building blocks such as mixers [3] and amplifiers [4] have been reported. This scenario leads to a demand for accurate compact models for circuit design engineers. These models have to cover not only the intrinsic device, but also the bias-dependent and performance-degrading extrinsic elements.

In this work we develop a compact model of the extrinsic part of a typical GFET structure. It is implemented in Verilog-A and usable with conventional circuit simulators. We assume a double-gate GFET structure with a channel of pristine monolayer graphene (Fig. 1). The intrinsic channel is covered by a high-κ/metal gate stack and modeled such as proposed in [5]. The extrinsic model consists of the contact resistances \( R_{m-g} \) and \( R_{g-c} \) at the metal-graphene interface, the access resistance \( R_c \) of the graphene contact layer between the electrodes and the intrinsic device, and fringe capacitances \( C_{c,x} \) between the electrodes and this graphene layer (Fig. 2).

\( R_{m-g} \) and \( R_{g-c} \) are due to two consecutive tunneling processes at the metal-graphene interface. In compact models these resistances have up to now been empirically approximated [6, 7]. We implemented them following the description of the underlying physical processes given in [8] and using a combination of power-law and linear curve fitting (Fig. 3). \( R_c \) is due to the finite resistance of the extrinsic graphene layer. In a novel approach we split this region into segments and consider each of them as an individual triple-gate GFET device, which is weakly coupled to the gate and source/drain electrodes as well as to the back-gate (Figs. 4 and 5). There is a low voltage drop over the individual segments, which implies Fermi-levels close to the Dirac point. We have developed a drain current description which is accurate under these low-voltage conditions and have validated it by comparison to experiments [9] (Fig. 6).

Simulations show that the extrinsic resistances have a strong impact on device current \( I_d \) (Fig. 7). When simply regarding the intrinsic device, a variation of the back-gate voltage \( V_{bs} \) only leads to a shift in the point of minimum current. By considering \( R_{m-g}, R_{g-c}, \) and \( R_c \), a decrease in \( I_d \) can be observed. An efficient method to mitigate these parasitic resistances is to induce additional charge carriers in the extrinsic graphene layer by increasing \( V_{bs} \) (Fig. 8). For instance, a change in \( V_{bs} \) from 0 to 20 V yields a decrease of the overall contact resistance from 5.49 to 2.18 kΩ·µm. These high \( V_{bs} \) values have been obtained for a back-gate oxide thickness of 300 nm. \( V_{bs} \) could be strongly reduced by for instance using a state-of-the-art FDSOI oxide thickness of 25 nm.

Based on these results, our work indicates the need for accurately modeling the GFET’s external resistances. Furthermore, applying a back-gate potential allows to significantly reduce them.

References


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Figures

Fig. 1: Cross-section of the modeled dual-gate GFET. The channel consists of pristine single-layer graphene and is connected to the electrodes with an extrinsic graphene layer.

Fig. 2: Equivalent circuit of the GFET showing extrinsic resistances and capacitances. The distributed model of the graphene contact layer is shown in a symbolized form.

Fig. 3: Contact resistance $R_{m-g} + R_{g-c}$ at the metal-graphene interface vs. Fermi levels $E_{fm}$ and $E_{fg}$ under the metal electrode and at the beginning of the extrinsic graphene contact layer, respectively. Curve fitting is used.

Fig. 4: Splitting of the graphene contact layer into $N$ segments. Each one is described as an individual weakly coupled GFET and modeled with high accuracy at low voltage drops.

Fig. 5: Segment-to-electrode outer-fringe capacitance $C_s$ for a geometry with $L_s = L_d = L_a = L_b = 1 \mu m$ and 100 nm contact height. Results were obtained with an EM field simulator and implemented in the model using power-law fitting.

Fig. 6: Low-voltage GFET model with high accuracy close to the Dirac point. A validation against measurement data for $V_{ds} = 10 \text{ mV}$ [9] shows a gain in accuracy close to the point of minimum current when comparing to previous models [5], [10].

Fig. 7: GFET transfer characteristics considering the metal-graphene contact resistance $R_{m-g} + R_{g-c}$ and graphene contact layer resistance $R_c$. The impact of both components, of only $R_c$, and of not considering any extrinsics is shown.

Fig. 8: Metal-graphene interface ($R_{m-g} + R_{g-c}$) and graphene contact layer ($R_c$) resistances at drain (solid line) and source (dashed line) side vs. back-gate voltage $V_{bs}$. Values are given for a back-gate oxide thickness of 300 nm.