

High-frequency performance of graphene field effect transistors with saturating IV-characteristics

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Abstract

High-frequency performance of graphene field-effect transistors (GFETs) with boron-nitride gate dielectrics is investigated. Devices show saturating IV characteristics and f_{\max} values as high as 34 GHz at 600-nm channel length. Bias dependence of f_T and f_{\max} and the effect of the ambipolar channel on transconductance and output resistance are also examined.

Introduction

Interest remains high in the potential use of graphene as a field-effect transistor (FET) channel replacement material [1, 2]. The focus is primarily on analog and RF applications of graphene FETs (GFETs) because of the limited on-current-to-off-current ratios achievable with this zero-bandgap material. Within the last few years, the RF performance of GFETs, as determined by the device current-gain cut-off frequency (f_T), has gone from 15 GHz [3] for 500-nm-length devices in the

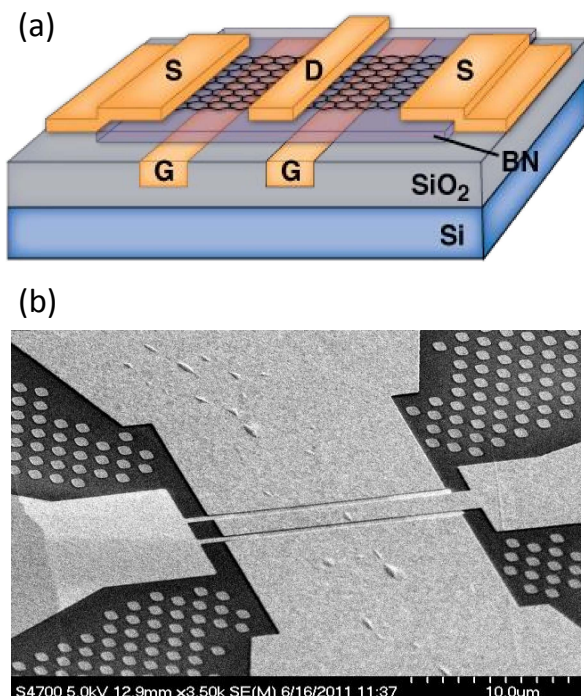


Figure 1. GFET device structure. (a) Schematic illustration of the back-gated GFET device. (b) SEM micrograph of a completed structure.

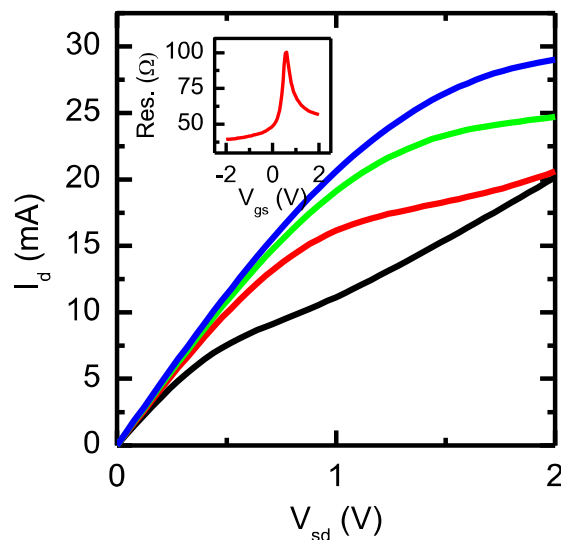


Figure 2. IV characteristics. I_D as a function of V_{sd} for V_{gs} from 0V to -1.5V in 0.5V steps. Inset: Resistance in linear transport region as a function of V_{gs} .

first measurements to 155 GHz at 40-nm channel lengths in the most recent reports [4].

RF measurements have generally been reported for top-gated

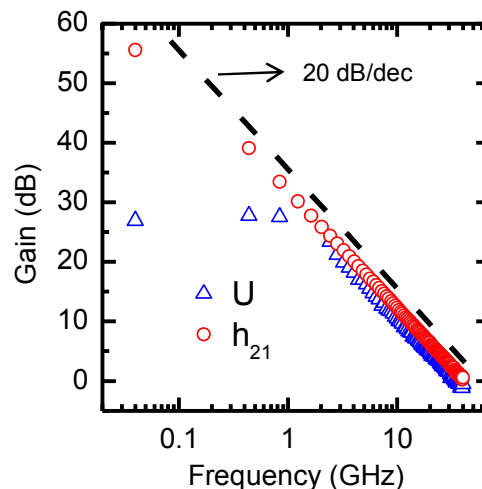


Figure 3. High-frequency device characteristics. h_{21} and unilateral power gain (U) as a function of frequency after deembedding, yielding $f_T = 44$ GHz and $f_{\max} = 34$ GHz.

device structures whose current-voltage characteristics do not show strong current saturation due to relatively poor gate-oxide interfaces or weak gate coupling. As a result, device output conductance is high, power gain is limited, and the maximum oscillation frequency (f_{max}) is typically only one-tenth of f_T . In this work, by exploiting high-quality boron-nitride dielectrics, we instead find f_{max}/f_T ratios as high as 0.86 and f_{max} values as high as 34 GHz for a 600-nm-length device, the highest value reported so far for GFETs. We further investigate the bias dependence of both f_T and f_{max} and compare our results with small-signal models of our device structures.

Device Fabrication

Hexagonal boron nitride (h-BN) has been previously found to be an outstanding gate dielectric for GFETs, yielding

interfaces nearly free of trapped charge and maintaining high mobility and carrier velocities in the graphene channel [5, 6]. The GFETs characterized here are created with a back gate as shown in Fig. 1a. A split-gate layout is employed, where tungsten metal gates are initially patterned into a 1- μm SiO_2 layer using a Damascene-like process, followed by a chemical-mechanical polishing (CMP) step to ensure a flat surface and expose the gate metal surface. h-BN (10-nm thick) is mechanically transferred to form the gate dielectric, followed by the mechanical transfer of the graphene channel (single layer). GFET fabrication ends with e-beam patterning of source and drain contacts with approximately 50-nm gate-to-source and gate-to-drain spacings as shown in Fig. 1a. An SEM micrograph of a completed device is shown in Fig. 1b.

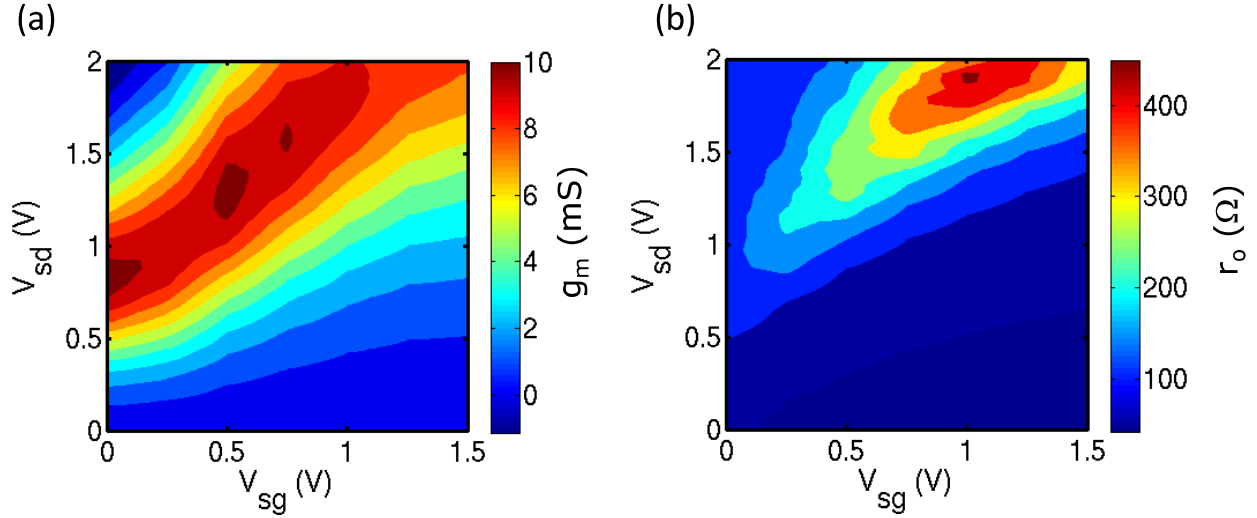


Figure 4. Bias-dependence of small-signal parameters. (a) Transconductance and (b) output resistance.

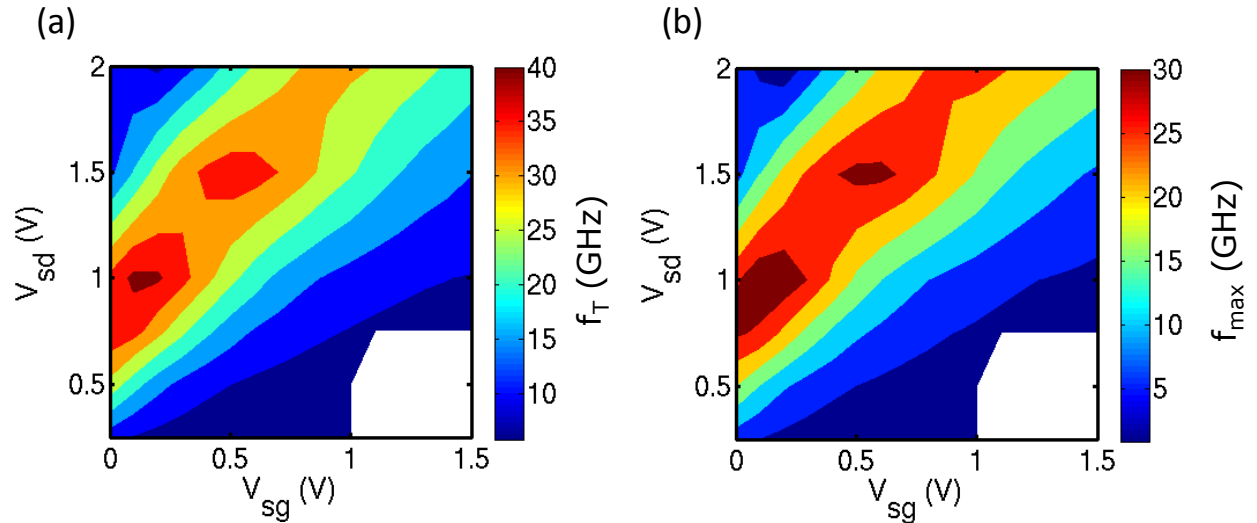


Figure 5. Bias dependence of high-frequency figures-of-merit. (a) f_T and (b) f_{max} .

DC Measurements

Fig. 2 shows the DC current-voltage (IV) characteristic of a representative GFET device with an effective width of approximately 38 μm and channel length of 0.6 μm . The inset of Fig. 2 shows the accompanying source-drain resistance in the triode region at $V_{sd} = 10$ mV, from which the contact resistance and low-field mobility can be extracted. The total contact resistance (including both source and drain) is approximately 25 Ω , or 950 $\Omega\text{-}\mu\text{m}$ when normalized to contact width. (Contact resistance is inversely proportional to contact width.) The low-field mobility is 3,300 $\text{cm}^2/\text{V sec}$. The charge neutrality point (V_o), the gate-to-source voltage at which the maximum low-field triode resistance is achieved, is 0.6 V. IV characteristics are plotted for gate voltages (V_{sg}) from 0 to -1.5V, demonstrating both saturating current characteristics for the unipolar hole channel and the “kink” associated with the transition to the ambipolar hole-electron

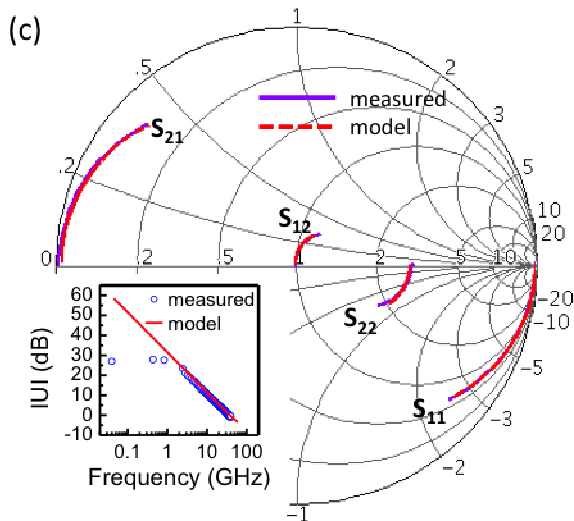
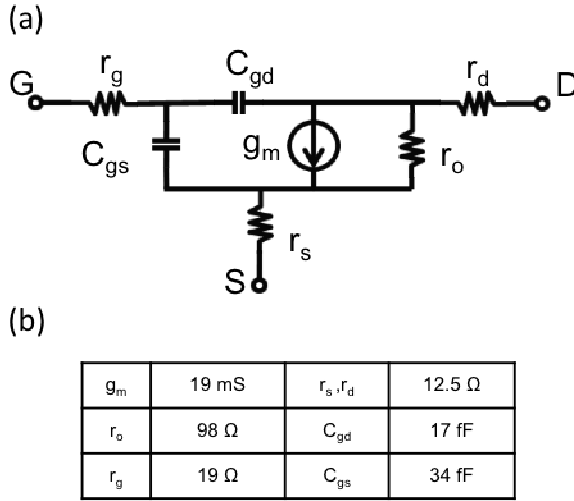


Figure 6. Small-signal modeling. (a) Small-signal equivalent circuit for a representative 0.6- μm transistors; (b) parameter values used in the model; and (c) measured S-parameters along with the results of the model. Inset: Unilateral gain of both measured and modeled device.

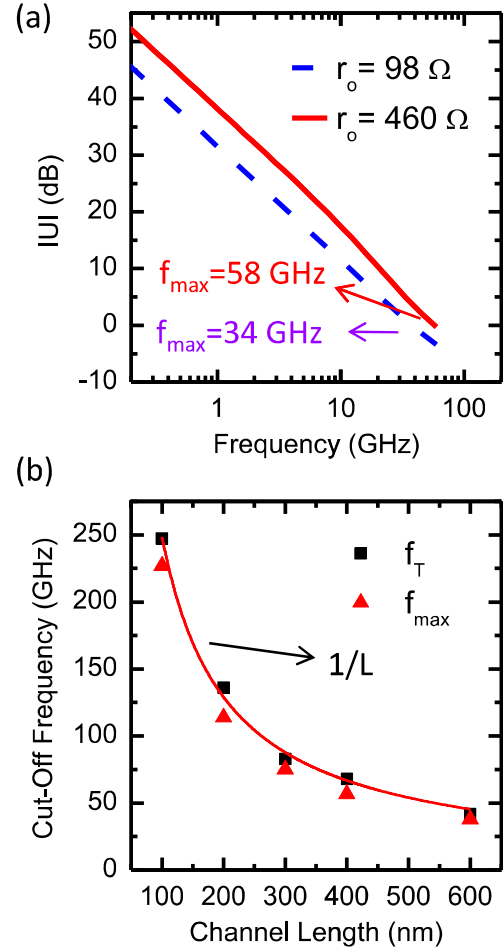


Figure 7. Improvements possible with device optimization. (a) U calculated from the model with parameter values of Fig. 6b (dashed blue) and with output resistance set to highest measured value (red). (b) Predicted high-frequency performance at different channel lengths.

channel. Fig. 4 gives the transconductance (g_m) and output resistance (r_o) as a function of bias; both are strongly influenced by the kink behavior in the IV characteristic. The peak g_m of 10.5 mS and peak r_o of 460 Ω occur at different bias points. The devices show no hysteresis and unchanged characteristics after repeated measurements.

High-Frequency Measurements

Device S-parameters are measured to 40 GHz. Standard “open-short” de-embedding methods are employed. In Fig. 3, current-gain (h_{21}) and unilateral power gain (U) are plotted at the bias point of peak g_m , yielding f_T and f_{max} of 44 GHz and 34 GHz, respectively. (Without de-embedding f_T and f_{max} are 24 GHz and 17 GHz, respectively.) Fig. 5 shows f_T and f_{max} as a function of bias; the peak high-frequency response closely matches the peak transconductance of the device.

The small-signal model of Fig. 6a is used to model the high-frequency behavior of the GFETs. The measured S-

parameters are shown in Fig. 6c, showing good agreement with the results of the small signal model with the parameters given in Fig. 6b. These small-signal values are in good agreement with values derived from the IV characteristics. The g_m here is the intrinsic value, exclusive of contact resistance, in good agreement with our previous results of approximately 0.5 mS/ μm [6].

The model derived from this representative 0.6- μm device can be used to further understand device optimization and scaling. Fig. 7a shows how the f_{max} performance could be improved to 58 GHz for this same channel length if the V_o of the device could be adjusted (through a secondary gate or channel doping) to align peak g_m and r_o . The model is also used to estimate the performance at shorter channel lengths by scaling gate capacitance while keeping other small-signal parameters constant as shown in Fig. 7b. f_{max} values close to 250 GHz are possible at 100 nm channel length. Higher frequency performance will require significant improvements in device parasitics, most notably the contact resistance.

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