Gigahertz Operation of Epitaxial Graphene Transistors

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The transport properties of graphene with saturation currents as high as 1.5 A/mm and electron mobilities of 15 000 cm^2/Vs [1] place this material in the limelight as an attractive candidate of next-generation nanoelectronic devices. While DC performance has been extensively studied just a few small signal characterizations have been done so far. The widely observed high carrier mobility naturally focuses our attention towards high frequency performance of graphene based devices. Gigahertz operation of exfoliated [2] and epitaxial [3] graphene FETs has been reported recently. Here we present the high frequency performances of graphene devices based on epitaxially grown graphene on SiC substrates. The measured $f_T \cdot L_G$ product of 8 GHz·μm and f_{max} of 16 GHz is in very good agreement with previously reported values [3]. Surprisingly, in spite of the much lower electron mobility and transconductance, these FETs demonstrate remarkable small signal performance comparable to the small signal performance of higher mobility exfoliated graphene devices.

We use epitaxial graphene on Si-face 4H-SiC. According to AFM characterization and Raman measurements the graphene thickness is 1.9 layers in average over the wafer [4]. We patterned the graphene by optical lithography and etched it in O_2 plasma. Using the same resist-pattern we etch 100 nm deep the SiC in CF_4 plasma to facilitate the sticking of the metal contacts on the surface. Cr/Au source/drain contacts and e-beam evaporated Al_2O_3/Ti/Au top gate (t_{ox} = 15 nm) have been deposited to form field effect transistors (FETs). For increased RF performance short gates were fabricated using e-beam lithography. The channel lengths of the devices range from 1 – 4 μm and the gate length is 1 – 2 μm in optically defined and 40 - 500 nm in e-beam patterned devices. Standard ground-signal-ground probing pads are lithographically realized for the gate and drain. Open structures were used to de-embed the signals of the parasitic pad-capacitance.

Hall measurements reveal $\mu \sim 200 – 500$ cm^2/Vs throughout the sample showing smooth variation and better performance in the middle of the wafer. The DC output characteristics of the devices were linear up to 5 V and slightly sublinear above 10 V. The drain current had a weak gate dependence as we swept the gate voltage between +/- 2.5 V. The gate modulation decreased as we drove the devices into high source-drain bias range indicating a non-reversible degradation mechanism by high electrical field. The conductance of the devices was varying between 3-7 mS, the transconductance was 120 – 400 μS/mm, which is significantly lower than in case of exfoliated devices.

Small signal performance of devices with gate-lengths between 2 μm and 0.5 μm on epitaxially grown graphene were measured. The used bias-conditions for the FETs are V_{DS} = 10 V and V_{GS} = 2 V. A deembedded current gain cut-off frequency f_T of 4.1 GHz for devices with 2 μm long gates was achieved. For a graphene FET with a 0.5 μm long gate an exceptional high power gain cut-off frequency f_{max} of 16 GHz is demonstrated. These preliminary results are very encouraging and demonstrate the potential of the epitaxially grown graphene devices for high-frequency applications as the quality of graphene on insulating substrates improve over time.

[1] A. K. Geim and K. S. Novoselov, Nature Materials 6, 183-191 (2007).
[2] Y-M. Lin, K. A. Jenkins, A. Valdes-Garcia, J. P. Small, D. B. Farmer and P. Avouris, Nano Lett. 9, 422–426 (2009).
[3] HRL Press announcement 12/15/2008. www.hrl.com
[4] Luxmi, S. Nie, P.J. Fisher, R.M. Feenstra, G. Gu, and Y. Sun, J. of Electr. Mat. DOI: 10.1007/s11664-008-0584-3. (2008)

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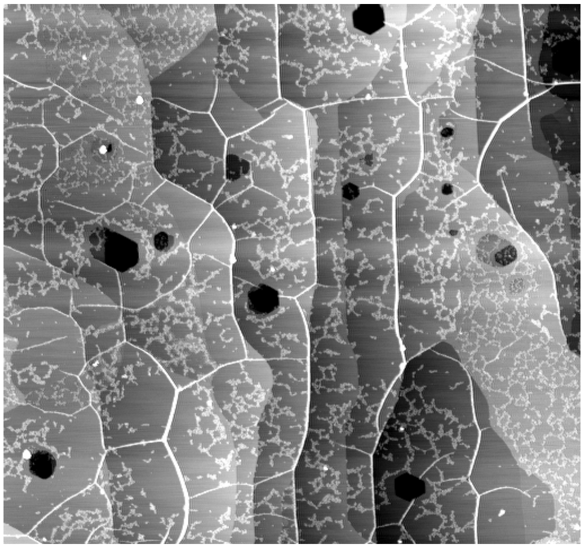

Fig. 1 AFM image of the graphene surface. 5x5 μm, gray scale range: 3.0 nm.

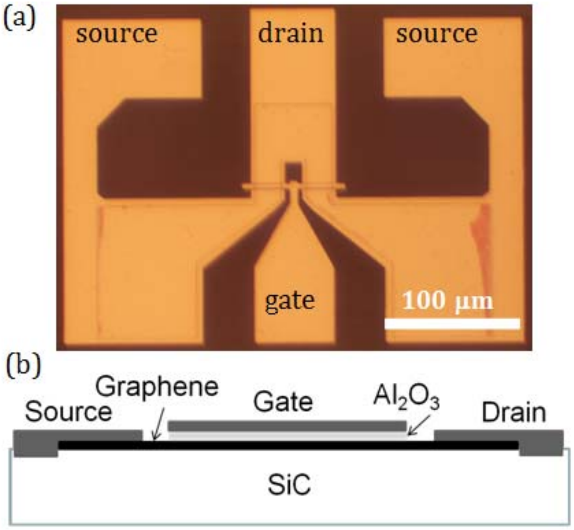

Fig. 2 (a) Optical image and (b) schematic cross section of the device structure.

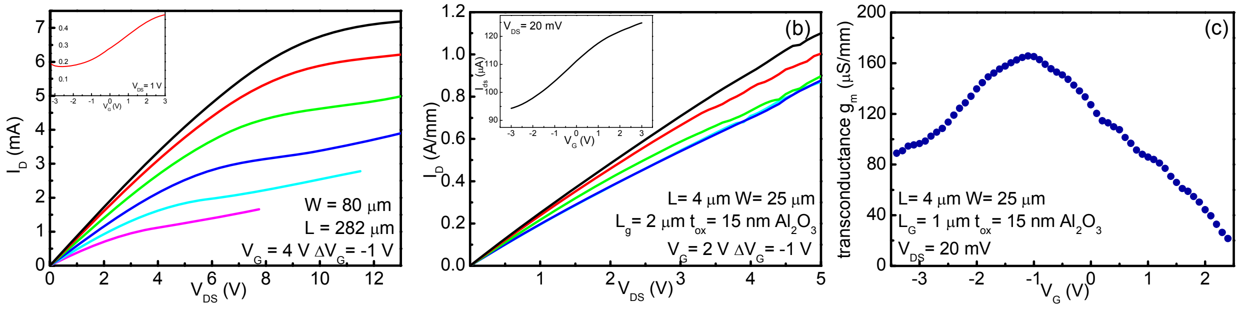

Fig. 3 (a) Output characteristics of a large area graphene transistor. Clear saturation can be observed. Inset: transfer characteristics at V_{DS} = 1 V. (b) Output characteristics of the graphene transistor, which RF characteristic is shown below. Inset: transfer characteristics at V_{DS} = 20 mV. (c) Transconductance as a function of gate voltage at V_{DS} = 20 mV.

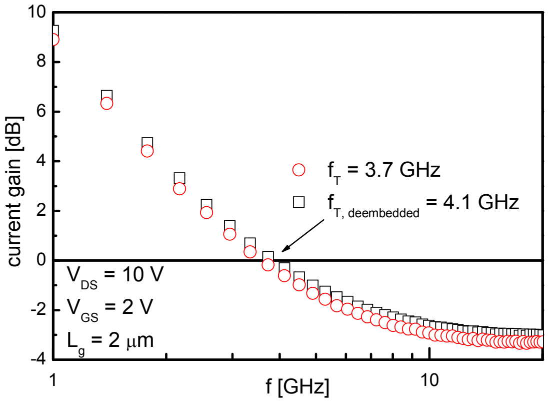

Fig. 4 Current gain as function of frequency for a graphene FET with 2 μm long gate.

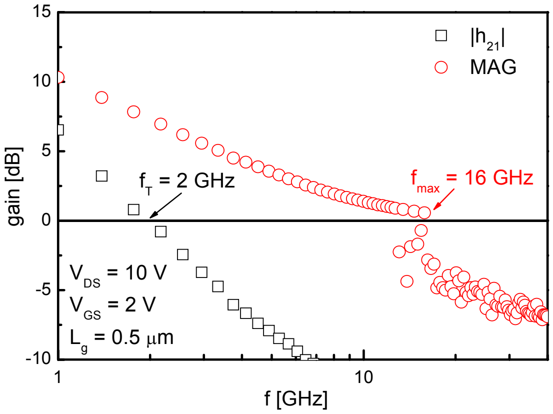

Fig. 5 f_T and f_{max} of a graphene transistor with 0.5 μm long ebeam-defined gate.