Transfer-Free Grown Bilayer Graphene Transistors with Ultra-High On/Off-Current Ratio

Pia Juliane Wessely[1]**,** Frank Wessely[1], Emrah Birinci[1], Bernadette Riedinger[2], Udo Schwalke[1]
[1] Institute for Semiconductor Technology and Nanoelectronics (ISTN),
Technische Universität Darmstadt, Schlossgartenstraße 8, 64289 Darmstadt, Germany
[2]Fraunhofer-Institut für Werkstoffmechanik, Wöhlerstraße 11, 79108 Freiburg, Germany

pj.wessely@iht.tu-darmstadt.de

1. Introduction

In this paper we report on monolayer graphene transistors (MoLGFETs) and bilayer graphene field effect transistors (BiLGFETs) which grow transfer-free on oxidized silicon wafers. By means of catalytic chemical vapor deposition (CCVD) in-situ grown MoLGFETs and BiLGFETs, respectively, are realized directly on oxidized silicon substrate, whereby the number of stacked graphene layers is determined by the selected CCVD process parameters, e.g. temperature and gas mixture.

First experimental evidence demonstrating the feasibility of this transfer-free graphene growth method has already been published in November 2009 [1, 2]. The results of a Fourier-analysis of transmission electron microscopy (TEM) data of a fewlayer graphene sample revealed the crystalline properties of the graphene multilayer more in detail as published in April 2011 [3]. In fact, the observed interplanar spacing of 3.5Å is a strong evidence for the existence of fewlayer graphene grown by means of CCVD. Furthermore, the combination of atomic force microscopy examination, Raman spectroscopy as well as extensive electrical characterization of graphene structures on silicon dioxide confirms the suitability of this novel in-situ CCVD growth process [4, 5, 6].

MoLGFETs exhibit the typically low on/off-current ratio of 16 and show the typical Dirac point. In contrast, BiLGFETs exhibit ultra-high on/off-current ratios of 10^7, exceeding previously reported values by several orders of magnitude. The transfer characteristic shows a pure unipolar p-type device behavior. Besides the excellent device characteristics, the complete CCVD fabrication-process is silicon CMOS compatible. This will allow a simple and low-cost integration of graphene devices for nanoelectronic applications in a hybrid silicon CMOS environment.

2. Results and Discussion

The electrical characterization of the graphene devices is performed using a Keithley SCS 4200 semiconductor parameter analyzer. The catalyst areas are simultaneously used as source and drain contacts [5]. An illustration of the device is shown in Fig. 1a. Fig. 1b shows the transfer characteristic of a MoLGFET. The current flow from source to drain (I_{DS}) is measured as a function of the applied backgate voltage (V_{BG}), swept from -15V to 15V and reverse, while a constant voltage between drain and source (V_{DS}) of 3V is applied. The Dirac-point at V_{BG} = -6V confirms the existence of electron and hole conduction as expected for graphene [7]. The electrical characterization of several MoLGFETs shows an average hysteresis value of $\Delta V_{BG,MoLGFET}$ = 16.8V ± 20% [6]. However, for in-situ CCVD grown graphene FETs the maximum current is limited by the thin nickel conducting paths as well as the high contact resistance caused by some carbon deposits on top of the source drain regions [5]. Fig. 1c shows the current voltage characteristics of a typical in-situ CCVD grown BiLGFET depending on the applied backgate voltage (V_{BG}), exhibiting an on/off-current ratio of $1x10^7$ at room temperature. Furthermore, when increasing the ambient temperature to 200°C, the on/off-current ratio only degrades slightly by one order of magnitude for BiLGFETs [8]. The needed bandgap is partly induced by the applied backgate voltage. Accordingly, we suspect that additional effects, like intensive interactions between bilayer graphene and silicon dioxide are responsible to further enhance the bandgap. Such intensive interactions may develop during the growth of the bilayer graphene on the silicon dioxide at moderate temperatures under well defined ambient conditions within a CVD chamber [5]. Since substantial amounts of atomic hydrogen are generated from the decomposition of methane during

CCVD processing, it is likely that hydrogen atoms adsorb on the graphene surface or may be incorporated within the graphene bilayer. As a result, effects on the electronic properties such as increasing the bandgap are expected. All BiLGFETs show a clear unipolar p-type device behavior which is consistent with the output characteristic [5]. The selection of the carrier type (i.e. holes in this case) may be facilitated by additional doping and/or Schottky-barrier effects [8]. In-situ CCVD grown BiLGFETs exhibit an average hysteresis of $\Delta V_{BG,BiLGFET}$ = 19.5V ± 20% [6]. The observed hysteresis corresponds well to results on graphene devices obtained from other research groups [9]. The hysteresis in both kind of transistors, i.e. MoLGFETs and BiLGFETs, is attributed to trapping and de-trapping of charges at the oxide-graphene interface [9].

3. Conclusions

BiLGFETs exhibit ultra-high on/off-current ratios of $1x10^7$ exceeding previously reported values by several orders of magnitude. We explain the improved device characteristics by a combination of effects, in particular graphene-substrate interactions, hydrogen doping and Schottky-barrier effects at the source/drain contacts as well. With this transfer-fee fabrication method hundreds of large scale BiLGFETs are realized simultaneously on one 2” wafer in a silicon CMOS compatible process.

Acknowledgement

This research is part of the ELOGRAPH project within the ESF EuroGRAPHENE EUROCORES program and partially funded by the German Research Foundation (DFG, SCHW1173/7-1).

References

[1] L. Rispal, U. Schwalke, SCS Trans., (2009)

[2] L. Rispal, P.J. Ginsel, U. Schwalke, ECS Trans., 33 (9) (2010), 13-19.

[3] P.J. Ginsel, F. Wessely, E. Birinci, U. Schwalke, IEEE DTIS (2011)

[4] P.J. Wessely, F. Wessely, E. Birinci, U. Schwalke, ECS Trans., (2011) in print

[5] P.J. Wessely, F. Wessely, E. Birinci, K. Beckmann, B. Riedinger, U. Schwalke, PhysicaE (2012), in print, http://arxiv.org/abs/1111.6397

[6] P.J. Wessely, F. Wessely, E. Birinci, B. Riedinger, U. Schwalke, Electrochemical and Solid-State Letters, 15 (4) K1-K4 (2012) in print

[7] F. Schwierz, Nature Nanotechnology, 5, (2010)

[8] P.J. Wessely, F. Wessely, E. Birinci, B. Riedinger, U. Schwalke, ECS Trans., (2012) in print

[9] H. Wang, Y. Wu, C. Cong, J. Shang, T. Yu, ACS Nano 4, 12 (2010)

Figures

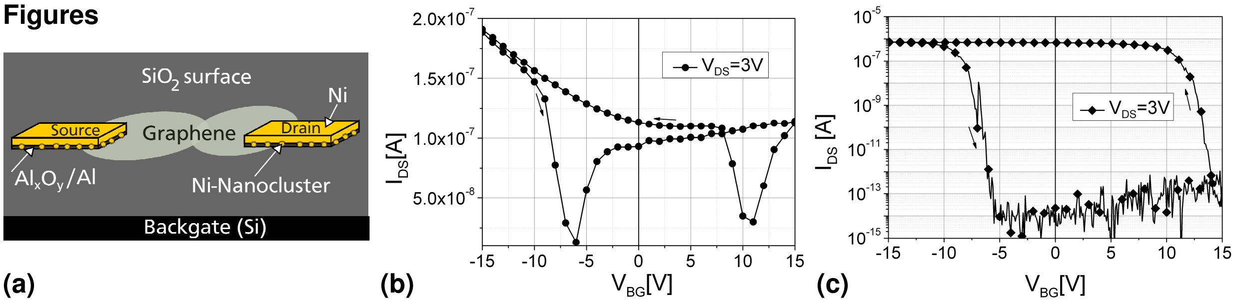

Figure 1: (a) Schematic drawing of a graphene field effect device structure produced by CCVD using an aluminum/nickel catalyst system. (b) Current voltage characteristic of a monolayer graphene transistor as a function of the applied backgate voltage V_{BG} exhibiting an on/off-current ratio of 16 at room temperature. (c) Current voltage characteristic of a bilayer graphene transistor as a function of the applied backgate voltage V_{BG} exhibiting an on/off-current ratio of $1x10^7$ at room temperature.