In-Situ CCVD Growth of Hexagonal Carbon for CMOS-Compatible Nanoelectronics: From Nanotube Field-Effect Devices to Graphene Transistors

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In this work, the in-situ growth of carbon nanotubes (CNTs) and graphene films directly on oxidized silicon wafers by means of catalytic chemical vapor deposition (CCVD) is demonstrated. In-situ means that the carbon structures are directly grown in their final position for device applications (cf. Figs. 1a and 2, respectively) so that tedious transfer and alignment procedures are obsolete.

Our CMOS compatible fabrication process for carbon nanotube field-effect transistors (CNTFETs) allows large scale production of good quality devices at low cost and within a short time. To achieve this, a dedicated in-situ growth method for single-walled nanotubes (SWNTs) has been developed, based on the catalytic chemical vapor deposition (CCVD) of carbon from methane. The major novelty of the process consists in the introduction of a sacrificial catalyst (i.e. well-optimized Ni/Al bilayer), which is evaporated on the whole wafer surface (see Fig. 1a), catalyzes the growth of 1 nm diameter SWNTs (see Fig. 1 c and d) and simultaneously transforms itself into an insulator (aluminum oxide covered with nickel nanoclusters) during the growth process at elevated temperatures (800 - 900 °C), so that there is no need to structure the catalyst after deposition. Only a single optical lithography step is needed to structure Pd source/drain contact regions for electrical characterization, allowing the simultaneous fabrication of approximately 1,000 transistors on one two-inch wafer even with non-optimized layout. Details on the self-aligned fabrication process have been reported previously [1, 2]. The suitability for mass fabrication of this process has been verified on more than 15,000 devices. Extended yield statistics on 700 devices have been performed, leading to the result of 41% of fully functional high on/off-current ratio devices, i.e. typical > 10^7 (see Fig. 1e) within all measured devices (see Fig. 1f).

On the basis of a modified in-situ CCVD growth process, first successful attempts of growing mono-, bi- and few-layer graphene films directly on oxidized Si-wafers have been performed (Fig. 2). In contrast to CNT growth, the aluminum only partially transforms into aluminum-oxide (Al_xO_y) [3]. Accordingly, the structured catalyst can be directly used as source and drain contacts for device characterization as illustrated in Fig. 2. Using the in-situ CCVD process several hundred graphene devices are realized simultaneously across one 2" wafer and are directly functional after the CCVD growth. These graphene devices possess a well defined channel length in the range of 1.6 µm to 5 µm while the channel width varies randomly from approximately 0.1 µm to several microns, depending on local growth conditions. The in-situ grown graphene layers extend only a few microns on the SiO_2 surface and therefore do not always fill up the maximum designed channel width. The number of grown stacked graphene layers depends on the adjusted process parameters, e.g. temperature and gas mixture and have been confirmed by AFM step-height measurements and TEM analysis [4]. In addition, Raman spectroscopy has been performed within the channel region in between the catalytic areas. The Raman data shown in Fig. 3 confirm the existence of few-layer graphene growth (Fig. 3a), most likely 5 layers, rather than e.g. amorphous carbon deposition during CCVD. Additional analysis of the shape and position of peaks G and D' indicate strong interactions of graphene with underlying SiO_2. These intensive interactions between graphene and SiO_2 are characteristic for our CCVD process due to the in-situ growth at high temperatures. Fig. 4 shows the transfer characteristic of a monolayer graphene field-effect device. The Dirac-point at V_G=-6V confirms the co-existence of electron and hole conduction as expected for graphene [5]. However, a slightly unsymmetrical current-voltage characteristic is noted in Fig. 4. Obviously, hole-conduction is preferred in our in-situ CCVD grown graphene, which appears typical for CVD-grown graphene according to Hall-effect measurements reported from other groups [6].

In conclusion, this successful demonstration of the in-situ catalytic growth of semiconducting CNTs and graphene layers provides a novel technological basis for integrated silicon-CMOS compatible carbon nanoelectronics.

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References

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Figures

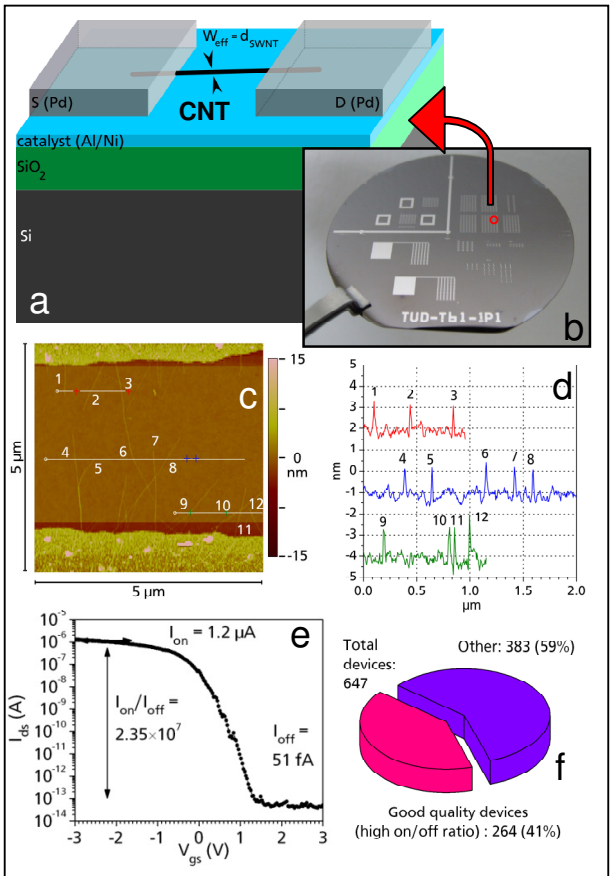

Fig. 1 a: Schematic of CNTFET.
b: Example of processed wafer with approx. 1000 devices.
c and d: AFM measurements (topographical scan and cross-sections) of in-situ grown CNTs showing their uniformity.
e: Example of transfer characteristic of high quality CNTFET with on/off-current ratio of > 10^7.
f: Distribution of high quality devices within ~700 nanotube devices

Carbon Nanotube Device Fabrication

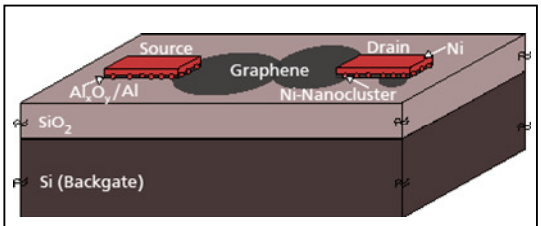

Fig. 2: Schematic drawing of in-situ grown graphene layer produced by means of CCVD using a nickel-aluminum catalyst.

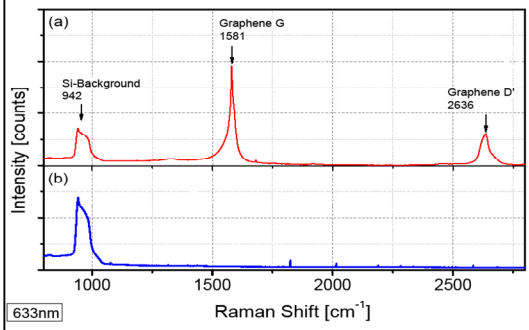

Fig. 3: (a) Raman spectrum of graphene (few-layer) measured within the channel region. (b) Raman spectrum measured in approximately 5µm distance to the channel region.

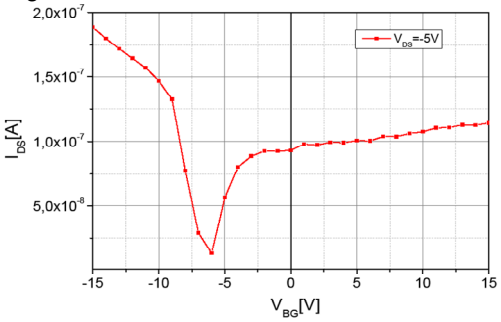

Fig. 4: Current-voltage characteristics of in-situ grown monolayer graphene. The Dirac point shows the conductivity of electrons and holes as well.

Graphene Device Fabrication