Graphene-Based Nanoelectronics

Frank Schwierz

Institut für Mikro- und Nanotechnologien, Technische Universität Ilmenau, PF 100565, 98684 Ilmenau, Germany
frank.schwierz@tu-ilmenau.de

1. Introduction

Two pioneering papers on the 2D (two-dimensional) carbon-based material graphene published in 2004 [1-2] ignited an enormous attention to this material and it did not take long before the electron device community showed interest in graphene [3-5]. Mainly graphene's excellent carrier transport properties have attracted device engineers and led to the expectation that graphene could be an ideal material for high-performance ultra-fast transistors. Already the early papers reported on room-temperature mobilities of 10^4 cm^2/Vs in graphene [1], and meanwhile mobilities exceeding 10^5 cm^2/Vs at 300 K have been measured in graphene [6].

Many groups worldwide started research on graphene transistors and in 2007 the first graphene MOSFET has been presented [7]. Since then, the performance of graphene MOSFETs could continuously be improved. In spite of this progress, however, so far graphene could not fulfill the high expectations and the main problems of graphene transistors are still not solved. Meanwhile part of the early excitement is gone and the potential of graphene for electronics is assessed less enthusiastic compared to the early days [8-9].

Another interesting aspect is that, virtually in the lee of graphene, a variety of other 2D materials has been discovered that may be of interest for electronics [10].

2. Graphene Transistors for Digital Logic

Current digital logic is dominated by CMOS. For any FET to be used in CMOS, good switch-off is mandatory, and switching a FET off inevitably requires a semiconducting channel with a sizeable bandgap (preferably 0.4 eV or above). Here, graphene faces a serious problem. Pristine large-area graphene is gapless and behaves like a semi-metal. A gapless MOSFET channel, however, cannot be switched off and therefore large-area graphene is not useful for CMOS. An option to open a gap in graphene is forming narrow GNRs (graphene nanoribbon). GNR MOSFETs with on-off ratios exceeding 10^6 have successfully been fabricated [11]. However, ribbons having a width well below 10 nanometers are needed for a gap ensuring good switch-off [4, 11] and this represents a serious processing challenge. Moreover, the gap opening in GNRs is accompanied by a dramatic mobility reduction and irregular ribbon edges deteriorate transistor performance.

Due to these problems, graphene MOSFETs for digital logic receded into the background recently and more attention is now paid to graphene RF (radio frequency) MOSFETs.

3. Graphene Transistors for RF Applications

RF FETs are usually operated in the on-state and do not need to switch off. Therefore, on first view, gapless large-area graphene might be a useful channel material for RF FETs. The first RF graphene MOSFETs have been reported in 2008 [12] and since that time many groups have realized graphene RF MOSFETs with large-area gapless channels. Figure 1 shows the best reported cutoff frequencies f_T (the frequency where the small-signal current gain drops to unity) of graphene MOSFETs together with the f_T performance of competing RF FET types.

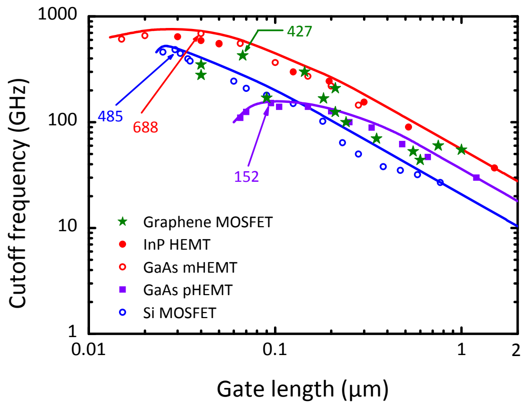

Fig. 1. Cutoff frequency of graphene MOSFETs vs. gate length, together with the f_T performance of competing RF FET types. The numbers indicate the record f_T's in GHz. Updated from [9].

As can be seen, in terms of f_T graphene MOSFETs outperform Si MOSFETs with comparable size and compete well with InP HEMTs and GaAs mHEMTs which are the fastest RF FETs at all. The current record for graphene is a f_T of 427 GHz achieved with a 67-nm gate MOSFET [13].

For most applications, the maximum frequency of oscillation f_{max} (the frequency where the transistor's power gain drops to unity) is more important than f_T. Unfortunately, regarding f_{max} the picture looks less promising for graphene MOSFETs. While, as shown in Fig. 2, the record f_{max} of III-V HEMTs exceeds 1 THz and Si MOSFETs with f_{max} of 420 GHz have been reported, the best graphene RF FETs show f_{max} of about 100 GHz only [14]. It has been discussed in detail that the main reason for the poor f_{max} performance of graphene MOSFETs is the unsatisfying saturation of the drain current which, in turn, is a consequence of the missing gap in large-area graphene [9]. This brings us to the conclusion that high-performance RF MOSFETs with competitive f_{max} need a channel with a gap.

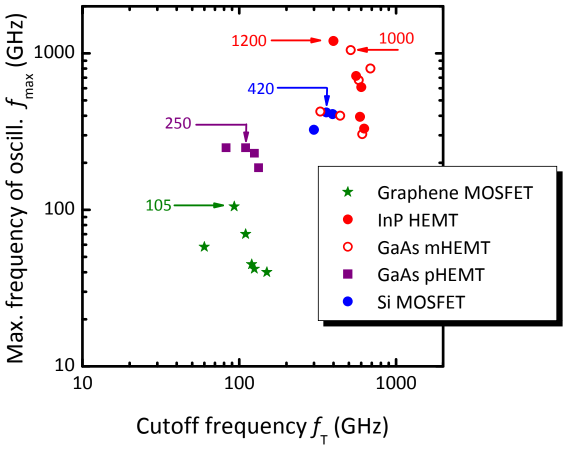

Fig. 2. f_{max} vs. f_T of graphene MOSFETs and competing RF FET classes. Updated from [15].

4. Outlook

So far we have presented a gloomy picture of the prospects of graphene in nanoelectronics. We should, however, not prematurely rule out graphene and the 2D materials beyond graphene. Instead, the following issues deserve consideration.

(i) When MOSFET scaling reaches the 5 nm gate length level, direct source-drain tunneling becomes a serious issue. Recent theoretical studies have shown that by using channel materials with heavy carrier effective mass (and thus low mobility), such as GNRs or 2D TMDs (transition metal dichalcogenide) like MoS_2, the tunneling currents can significantly be suppressed [16-17]. Thus, GNRs and 2D TMDs can possibly extend the lifetime of MOSFET scaling and Moore's Law beyond the limits of Si.

(ii) There are transistor concepts beyond the MOSFET that can be realized with graphene. For example, the vertical graphene base transistor [18] and the BiSFET (bilayer pseudospin FET) [19], for which the missing gap does not represent a problem, have been proposed.

(iii) Semiconductor electronics comprises more than merely digital logic and RF. Since graphene and other 2D materials are bendable, they show promise for the emerging field of flexible electronics [20], to name just one example.

Thus, we conclude with the optimistic remark that research on graphene and the 2D materials beyond graphene has not nearly reached its limits and will stay exciting for many years to come.

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