Performance Evaluation of Graphene Nanoribbon Tunneling Field Effect Transistors

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1. Introduction

With aggressive device miniaturization, conventional complementary metal-oxide semiconductor (CMOS) transistors based on silicon are rapidly reaching their fundamental physical limits and novel device structures are required. Many studies had shown that silicon tunneling field-effect transistors (TFETs) have a smaller (<60mV/dec) subthreshold swing which is ideal for fast switching applications, and a lower OFF current (I_{OFF}) which can be used for low power devices. However, due to the dependency of tunneling mechanism, the ON current (I_{ON}) is too small and novel electronic materials which have high carrier mobility can be used to improve the performance of TFET [1-3]. In this regard, alternative electrical material can be used, such as graphene related materials, which have attracted a lot of attention in the device community recently since the physical realization of thermodynamically stable graphene sheets. More specifically, the one dimensional graphene nanoribbons (GNRs) which inherited the excellent electrical properties of the planar graphene sheet such as high carrier mobility [4], as well as exhibiting some of their own unique properties such as the variation of energy gap by change the ribbon width [5], can be a good material for TFET implementation. While previous computational studies on GNR TFET such as Zhang, et al [6] which employed the WKB approximation were not able to properly capture the full quantum tunneling event, utilization of π-orbital tight-binding method as in Zhao et al. [7] requires a large amount of computational resources and inhibits the investigations of larger system. As such, a mode-space quantum simulator based on the Dirac equation is developed for the study of GNR TFET and in this work, we present our computational study on the device characteristics of GNR TFET at different ribbon width and doping concentrations.

2. Simulation model

A side view schematic of the device structure used in the simulation is shown in Fig. 1(a) which is similar to a double gate CMOS device, with the device material replaced with GNR. The width (W) of the GNR (shown in Fig. 1(b)) is an important parameter for GNR devices and three different widths are studied in this work. A quantum simulator, which couples the Dirac equation [8] that describes the electronic interaction in GNR, with the non-equilibrium Green’s function approach [9], is used to simulate the carrier transport of the GNR TFET. This novel method, which we termed Dirac tight-binding, is first validated by calculating the energy spectra of GNRs with different widths and comparing them to π-orbital tight-binding calculations. The spectra are shown in Fig. 2 which exhibit matching results at low k-vectors for the widths of (a) 1.1, (b) 1.2 and (c) 1.3 nm. After the model validation, full device simulations, with the Poisson’s potential solved self-consistently, for devices with different widths and a similar channel length of 10nm, are carried out at a drain bias of 0.6V to extract the l_D50-V_GS current characteristics. For the 1D GNR TFET, the contacts have a carrier doping concentration of 0.71/μm, with the source doped with holes and the drain with electrons to simulate a p-i-n structure.

3. Results and discussion

As shown in Fig. 3, although the width is varied slightly from 1.1nm to 1.3 nm, the performance changes dramatically. The l_D50/I_{OFF} ratio changes from 1.87×10^3 to 4.36×10^2 to 1.10, and SS changes from 74 to 43 mV/dec to infinity for 1.1, 1.2, and 1.3nm wide GNR FETs, respectively. This variation can be explained by the change in the energy band gap as the width changes as shown in Fig. 2. The bandgap of 1.2nm cases is 1.2 eV while that of 1.3nm GNRs drops to 0.17 eV. We next focus on device physics of GNR TFETs and the local current spectra (I_k) are plotted for different gate bias (V_GS) of 0, 0.3 and 1V and are summarized in Fig. 4. At V_GS=0V, there is a high tunneling
current [arrow in Fig. 4(a)] from the channel to the drain due to the proximity between the top of the valance band (E_{CV}) of the channel and the bottom of the conduction band (E_{CV}) at the drain. This is commonly known as band-to-band tunneling (BTBT). As V_{GS} increases, the E_{C} and E_{V} at the channel-drain interface is being pulled apart and the BTBT at the drain side decreases and at V_{GS}=0.3V, the current is mainly due to the direct tunneling between the source and the drain, indicated by the arrow in Fig. 4(b). As V_{GS} increase further, the E_{C} of the channel is pulled below the E_{V} of the source and BTBT occurs at the source-channel interface [cf. arrow in Fig. 4(c)]. Therefore, in 1.1nm cases, the bandgap is too small to separate these different phenomena and results in the constant high current.

The effect of ribbon width on the device performance is also investigated and it is found that the device current at V_{GS}=1V shown in (c).

Lastly, the effect of different source doping concentration can be easily tuned by varying the doping concentrations at the source and drain. Hence the device performance of GNR TFET can be increased by increasing the doping concentration at the source and the OFF can be decreased by lowering the doping concentration at the drain. Hence the device performance of GNR TFET can be easily tuned by varying the doping concentrations at the source and drain.

4. Conclusion

The device characteristics of GNR TFET simulated with a Dirac tight-binding approach is presented in this work. The effect of ribbon width on the device performance is shown and it is found that a slight variation in width will have a vast effect on the I_{ON}/I_{OFF} ratio as well as the SS. The doping effects at the source and drain of GNR TFET are also investigated and it is found that the I_{ON} can be increased by increasing the doping concentration at the source and the I_{OFF} can be decreased by lowering the doping concentration at the drain. Hence the device performance of GNR TFET can be easily tuned by varying the doping concentrations at the source and drain.

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References