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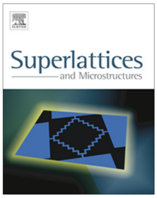

A computational study on electrical characteristics of a novel band-to-band tunneling graphene nanoribbon FET

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ABSTRACT

In this study, a modified structure was proposed for the band-to-band tunneling field-effect transistor (BTBT–FET) mainly to suppress the ambipolar current with the assumption that the ON state characteristics, especially sub-threshold swing, must not be degraded. The proposed structure uses a dual-material gate as gate contact and a narrow lightly doped region at the drain side of the channel. Electrical characteristics of the proposed device were explored by a mode-space non-equilibrium Green's function (NEGF) formalism in the ballistic limit. A significant reduction in the ambipolar current was seen in simulation results for different values of the drain–source voltages. The results also revealed that the ON current remained the same and the sub-threshold swing got slightly better than that of the main structure. The comparison with the main structure showed that the proposed structure benefited from improved switching characteristics such as delay, switching power-delay product and I_{ON}/I_{OFF} ratio. Further comparison indicated that the new structure had improved hot electron effect.

1. Introduction

In recent years, numerous studies have been done to find new materials, which can replace silicon in next-generation electronic devices. Graphene is one of the materials that has generated great

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interest due to its special electronic, mechanical, optical and thermal properties [1–3]. Because of its zero bandgap, graphene is used in the form of nanotubes (CNT) [4,5] and nanoribbons (GNRs) [6,7], the bandgaps of which can be tuned. A lot of work has been done on the use of CNTs as the channel of the field-effect transistors (FETs) [8–10]. Throughout the results, the proposed FETs can be categorized into three groups of Schottky-barrier FETs, tunneling FETs and MOS-Like FETs. All these structures can be constructed using GNRs with almost similar behaviors [11–13]. The last type acts as a conventional MOSFET and the current flow in the ON-state is dominated by the thermionic emission. Unfortunately, MOS-like FETs suffer from high leakage current resulted from the band-to-band tunneling (BTBT) of the carriers.

In the n-type (p-type) MOS-Like transistors, the current in the ON and OFF states is produced by the thermionic emission of the electrons (holes) and the BTBT of the holes (electrons), respectively. This phenomenon, in which there are two types of carriers in the transistor current but at different bias conditions, is called ambipolarity property, which is a serious problem for the use of transistor in the CMOS topology, in which both n-type and p-type transistors work together. In this situation, both transistors remain ON in any switching event, one by thermionic emission current and another one by the BTBT current (also called ambipolar current).

Some works have tried to suppress the BTBT phenomenon so that the MOS-Like topology could be used in this situation [14–17]. Although the thermionic emission limits the sub-threshold swing (SS) of MOS-Like FETs to 60 mV/dec, it has been demonstrated that these transistors show lower SS in the BTBT region [18]. Then, it was proposed to use the MOS-Like FETs in the reverse mode [18]. That is, the ON-state of the MOS-Like FETs is used as the OFF-state of the new transistors and vice versa. Such a transistor, which has a structure exactly identical to the MOS-Like FET has been named BTBT–FET. This is because, in contrast to the MOS-Like FETs, the ON current is now generated by the BTBT phenomenon. To be further specified, let us consider an n-type MOSFET, which, as we know, that turns on and off at $V_{GS} > 0$ and $V_{GS} < 0$, respectively. This transistor can be also used as a BTBT–FET. In this case, it will be turned on and off at $V_{GS} < 0$ and $V_{GS} > 0$, respectively. Note that for all the above-mentioned situations, V_{DS} is positive. Low SS, which is an important parameter for ultra-low-power applications, is the main advantage of the BTBT–FETs in comparison with the other structures.

Unfortunately, the BTBT–FETs also suffer from the ambipolar current even more than the MOS-Like FETs. Thermionic emission leads to high leakage current, which should be suppressed in order for this structure to be actually used in the CMOS topology. Yet, up to the present time, no modified structures have been proposed. In this paper, a structure was introduced mainly to suppress the ambipolar current of the BTBT structures. The results showed that it not only strongly suppressed the thermionic emission of the carriers but also showed the same ON-state current and SS as the main BTBT–GNRFET structure. The simulation results also indicated that the proposed structure benefited from the improved switching characteristics and hot-electron effect compared to the original structure.

2. Device geometry

A cross section of the proposed structure and the conventional BTBT–GNRFET are shown in Fig. 1.

The devices were composed of an armchair carbon nanoribbon with $n = 12$ and a width of 1.35 nm, which was sandwiched by HfO_2 as the dielectric layer with 1.5 nm thickness and relative dielectric constant of $\varepsilon_r = 16$. The n-type source and drain contacts were uniformly doped with a high doping concentration of 0.01 dopant per carbon atom.

As can be seen from the figure, two modification were made in the original structure, first, the gate contact was replaced by a dual-material structure, and the second, a lightly doped region was used on the drain side of the channel. The gate contact on the drain side of the channel has a higher work function to suppress the flow of thermal emission current. The part of the channel placed beneath the high work function material acted as a barrier in front of thermal emission of the carriers and significantly improved the ambipolar behavior of the transistor. Unfortunately, the switching speed was also degraded using this dual material gate structure. Because of using a higher work function material on the drain side of the channel, the tunneling region on the drain side was thinner compared to the main structure. Then, a lightly doped region could be used on the drain side of the channel for the purpose of