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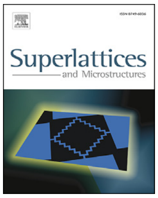

Oxide thickness-dependent effects of source doping profile on the performance of single- and double-gate tunnel field-effect transistors

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ABSTRACT

Operated by the band-to-band tunneling at the source-channel junction, the source engineering has been considered as an efficient approach to enhance the performance of tunnel field-effect transistors (TFETs). In this paper, we report a new feature that the effects of source doping profile on the performance of single- and double-gate germanium TFETs depend on equivalent oxide thickness (EOT). Based on the numerical simulations, it is shown that the effect of source concentration on the on-current is stronger with decreasing the EOT, particularly in the double-gate configuration due to the higher gate control capability. Importantly, when the EOT is decreased below a certain value, abrupt source-channel junctions are not only unnecessary, but gradual source doping profiles even improve the performance of TFETs because of the increase in vertical tunneling generation. With the continuous trend of scaling EOT, the oxide thickness-dependent effects of source doping profile should be properly considered in designing TFET devices.

1. Introduction

In the era of portable electronic devices, high energy efficiency is one of the most important requirements for a transistor to be used as a fundamental component in integrated circuits. A highly energy-efficient transistor is necessary not only to ensure the low-power consumption but also to resolve the power density problem of highly-scaled integrated circuits [1,2]. The essential advantage that makes tunnel field-effect transistors (TFETs) suitable for low-power applications is the breakthrough in the subthreshold swing limit of 60 mV/decade which is the physical limit of traditional metal-oxide-semiconductor field-effect transistors (MOSFETs) [3,4]. The steep on-off switching of TFETs allows of scaling down the supply voltage and associated dynamic power consumption. In order to establish the conduction state, however, valence electrons in TFETs have to tunnel through an energy barrier formed by the forbidden gap of semiconductors to become free carriers on the conduction band [3,5]. Since the probability of band-to-band tunneling (BTBT) is relatively low, TFET devices suffer from low on-current which is the most difficulty in applying them to practical uses [5,6]. Many relevant techniques based on minimizing the tunnel barrier have been proposed to ameliorate the on-current, such as device parameter optimizations [7,8], low-bandgap materials [9,10] and advanced TFET structures [11,12]. The excellent combinations of those techniques have also been considered to boost the on-current most effectively [13,14].

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For a given TFET structure, in general principle, the on-current is usually only improved by shortening the tunneling path of electrons at on-state to increase the tunneling probability [7]. Since the on-state tunneling is generated at the source-channel junction, there are two basic factors that mainly determine the tunnel barrier width in TFETs, including the source doping profile and equivalent oxide thickness (EOT). The source profile composed of doping concentration and gradient directly decides the tunnel width [8,15], whereas the EOT indirectly affects the tunnel width through the gate-controlled field [7]. Both theoretical and experimental researches have shown that the on-current is increased with increasing the source concentration because of the narrowed tunnel width [9,15]. A similar conclusion has also been made for the effect of source junction abruptness, i.e., the steeper the lateral doping gradient of source, the higher the on-current is [16,17]. For the effect of EOT, experimental results have confirmed the theoretical and numerical predictions that decreasing EOT helps to significantly increase the on-current because a higher gate control capability results in a smaller tunnel width [18]. Those conclusions have been demonstrated to be appropriate for both homo- and hetero-junction, high- and low-bandgap, single- and double-gate TFETs [8,9,15–18]. It is important to note that the conclusions on the effects of source doping profile do not depend on the EOT because the roles of source doping profile and EOT have been examined independently. In other words, the EOT was kept constant when studying the effects of source doping profile. However, while the tunnel width in TFETs is directly governed by the source doping profile, the EOT also concurrently determines the tunnel width. Therefore, the effects of source doping profile probably depend on the EOT.

In this paper, the dependence of the source profile effects on the EOT is numerically examined in single- and double-gate TFETs by using two-dimensional device simulations [19]. The physics of the oxide thickness-dependent effects is properly clarified to provide a comprehensive understanding on the mutual roles of the source profile and EOT in designing TFET devices. Both single- and double-gate structures are investigated because the control capability of the gate to the channel depends considerably on the gate structure which exhibits a role similar to the EOT in term of determining the gate control capability. Furthermore, the investigations of single- and double-gate TFETs are presented in parallel for convenient comparisons. The paper consists of five sections, including the Introduction (section 1) and the Conclusion (section 5). Section 2 first describes the device structures, physical models used in the simulations and then preliminarily inspects the role of EOT in the different TFET structures. The effects of source doping concentration on the performance of TFETs with a wide range of EOT are appropriately investigated in section 3, whereas section 4 is devoted to proper discussions on the oxide thickness-dependent effects of source doping gradient.

2. Device structures and physical models

Fig. 1 shows the schematic views of homojunction Ge TFETs with single- and double-gate structures. Since using low-bandgap semiconductors has been realized as the most effective technique to enhance the on-current of TFETs, low-bandgap Ge was adopted for the practical significance of the investigations. To exactly filter out the mutual effects of source doping profile and EOT, a typical homojunction structure was chosen to exclude the influences of material and structure parameters. The single- and double-gate structures were investigated in parallel because their different gate control capabilities may lead to the significantly different roles of the source profile and EOT. A long n-channel with a 150 nm length and 10^{17} cm^{-3} concentration was utilized to avoid short-channel effects which may cause difficulties in studying the impacts of the source profile and EOT on the TFET performance. The drain of TFETs was lightly doped with a donor concentration of 5×10^{18} cm^{-3} for minimizing the ambipolar off-leakage [15]. The EOT of high-k gate-dielectric $\mathrm{HfO_2}$ and the source profile including doping concentration and gradient were appropriately altered for studying purposes. The dielectric constant was varied to change the EOT while the physical oxide thickness was intentionally fixed at 3 nm to retain the identical fringing

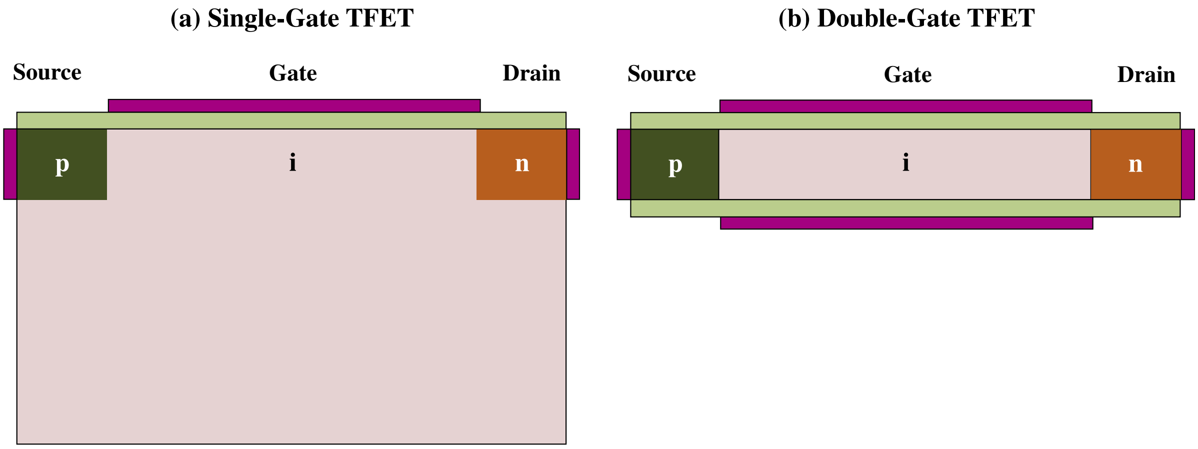

Fig. 1. Schematic structures of (a) single-gate (SG) and (b) double-gate (DG) TFETs using low-bandgap germanium.