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Modeling the impact of junction angles in tunnel field-effect transistors

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ABSTRACT

We develop an analytical model for a tunnel field-effect transistor (TFET) with a tilted source junction angle. The tunnel current is derived by using circular tunnel paths along the electric field. The analytical model predicts that a smaller junction angle improves the TFET performance, which is supported by device simulations. An analysis is also made based on straight tunnel paths and tunnel paths corresponding to the trajectory of a classical particle. In all the aforementioned cases, the same conclusions are obtained. A TFET configuration with an encroaching polygon source junction is studied to analyze the junction angle dependence at the smallest junction angles. The improvement of the subthreshold swing (SS) with decreasing junction angle can be achieved by using thinner effective oxide thickness, smaller band gap material and longer encroaching length of the encroaching junction. A TFET with a smaller junction angle on the source side also has an innate immunity against the degradation of the fringing field from the gate electrode via a high-*k* spacer. A large junction angle on the drain side can suppress the unwanted ambipolar current of TFETs.

1. Introduction

Miniaturization of electronic devices and scaling of the power supply have been following the complementary metal–oxide–semiconductor (CMOS) scaling rules for several generations [1]. The continued reduction of the physical dimension results in an increased leakage current due to short channel effects, such as drain-induced barrier lowering (DIBL). The off-state leakage current is also increasing due to the nonscalability of the threshold voltage restricted by the thermionic subthreshold swing (SS) limit of 60 mV/decade at room temperature [2]. Therefore, power consumption is becoming one of the most important challenges, and devices that are not subject to this fundamental physical SS limit are particularly attractive.

The tunnel field-effect transistor (TFET) is one of the devices that can reach sub-60 mV/decade SS since the off-current of a TFET mainly consists of p-i-n diode leakage and the injection mechanism into the channel is based on band-to-band tunneling (BTBT) [3–8]. Having a higher doping level and doping abruptness at the source-channel junction where the tunneling events take place gives rise to a higher tunneling current [9]. This source-channel junction typically has an angle nonorthogonal to the gate oxide/semiconductor interface. This is the case when ion implantation is used, when the junction is part of a nanowire (NW) grown by selective epitaxial growth (SEG) (see Fig. 1a), or when the junction is formed by silicidation induced dopant segregation [10]. However, most simulation and modeling works have been based on a doping junction normal to the gate oxide. In addition, Ref. [10] has experimentally shown that the tilted junction has a significant impact on the TFET performance, in particular on the onset of tunneling and the on-current. Even though an initial simulation-based investigation on the shape of the source doping has been made [11], more detailed physical insight is required.

In this paper, we start with the derivation of an analytical model for the tunnel current as a function of junction angle in Section 2. The implementation of device simulations and the model-simulation comparison is discussed in Section 3. In Section 4, we optimize the junction angle and in Section 5, we discuss the impact of the fringing field and the impact on the TFET's ambipolarcurrent.

2. Analytical model derivation

The existing analytical model for both n-channel TFET (nTFET) and p-channel TFET (pTFET) with a source-channel junction orthogonal to the gate oxide is based on an electrostatic potential profile analysis [12]. We use the same framework as well as the six assumptions made in Ref. [12] to describe the TFET with a junction

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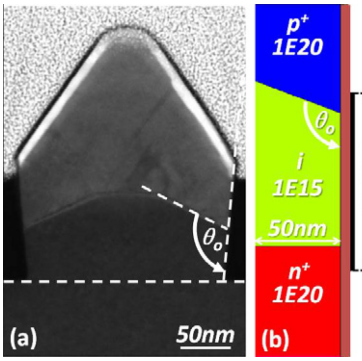

Fig. 1. (a) TEM image of a NW with facets formed by SEG. (b) The in simulations used nTFET configuration with a junction angle θ_o. The SiO_2 gate oxide is 2 nm thick.

angle θ_o (see Fig. 2), whereby the angle θ_o is defined as the angle between the interfaces of oxide-channel and source-channel. Briefly summarized, the six assumptions are that (1) the drain voltage does not affect the electrostatic profile in the source-channel region, (2) that the source doping is infinitely high resulting in no potential drop in the source, (3) that no (inversion) charges are present in the channel, (4) that no charges are present in the gate oxide, (5) that the oxide t_{ox} can be replaced with an equivalent oxide thickness $t_{eq} = t_{ox} * k_c/k_{ox}$ (where k_c and k_{ox} are the permittivity of the channel material and gate oxide, respectively), whereby the latter results in an electrically identical potential profile in the channel and smooth equipotential lines at the oxide-channel interface and (6) that the source electrode extends along the gate dielectric all the way to the gate electrode, ensuring that circular electric field lines are generated between source and gate electrode [12].

According to this framework, the electrostatic potential V of each straight equipotential line in the channel region is linearly proportional to the angle θ:

$$V(\theta) = \frac{\theta}{\theta_o}\psi_g; \quad 0 \leqq \theta \leqq \theta_o \tag{1}$$

The equipotential lines run through the corner C, with the leftmost equipotential line at the source-channel interface corresponding to the source potential 0 V ($\psi_s = 0$) and the equipotential line at the gate electrode corresponding to the gate potential $\psi_g = V_{gs} - V_{FB}$ with V_{gs} the gate-source bias and V_{FB} the flat band voltage of the doped source region. When the energy difference between two arbitrary equipotential lines is equal to one band gap E_g, an electron has a nonzero tunneling probability to tunnel from the valence band to the conduction band. According to Eq. (1), the angle θ_t between two such equipotential lines is given by:

$$\theta_t = \frac{E_g}{q\psi_g}\theta_o \tag{2}$$

where q is the elementary charge.

As a fully quantum mechanical treatment of band-to-band tunneling providing a rigorous calculation of the transmission probabilities is beyond the scope of this paper, we have adopted a semi-classical description that relies on the concept of point-to-point tunneling and the choice of an associated tunnel path. The choice of tunnel paths has a significant impact on the predicted TFET performance [13–16]. We consider three choices for tunnel paths: either a tunnel path along the electric field line, to benefit from the associated band bending, or a straight tunnel path, to capture the shortest possible point-to-point connection, or a tunnel path given by the classical trajectory of an electron/hole, as determined by the classical equations of motion arising from Newton's equation with a force derived from the electrostatic potential [13]. The latter choice is dependent on the initial velocity of the particle and a statistical distribution function over all allowed initial velocities should be accounted for, giving rise to a variety of tunnel paths. Given that a full study determining the most correct semi-classical implementation of tunneling trajectories is beyond the scope of this article, a single tunnel path corresponding to zero initial velocity is proposed for simplicity. Throughout the article, we will emphasize how the choice of tunnel path impacts the conclusions and which conclusions are independent of this choice.

2.1. Tunnel path calculation

A mathematical formula is determined for the length of the first two tunnel path choices. Two options are considered for the straight tunnel path choice, namely the shortest straight path and the shortest straight path parallel to the gate oxide. When considering a circular tunnel path, along the electric field $\vec{E}$, and $R_1 \geqq R_2$, as shown in Fig. 2a and b, the shortest tunnel path ends at point B, which is at the crossing of the oxide-channel interface with the equipotential line $V(\theta_t)$. The length of the shortest circular path can be written as

$$L_{cir}^{R_1 \geq R_2} = R_1\theta_t = t_{eq}\left[\frac{\theta_t}{\sin(\theta_o - \theta_t)}\right]. \tag{3}$$

In case $R_1 \leqq R_2$, as shown in Fig. 2c, the length of the shortest circular path along the electric field, which now starts and ends in the channel region, can be written as

$$L_{cir}^{R_1 \leq R_2} = r_2\theta_t = t_{eq}\left[\frac{\theta_t}{\cos(\theta_t/2)}\right]. \tag{4}$$

When considering straight tunnel paths, the length of the shortest straight tunnel path can be written as

$$L_{strai}^{\theta_0 \leq 90^\circ} = R_1 \sin\theta_t = t_{eq}\left[\frac{\sin\theta_t}{\sin(\theta_0 - \theta_t)}\right], \tag{5}$$

for $\theta_o \leqq 90°$, (see Fig. 2a), with the length of the shortest straight tunnel path parallel to the gate oxide, running from point A to point B, given by:

$$L_{ox/channel} = \overline{AB} = t_{eq}\left[\frac{1}{\tan(\pi - \theta_o)} + \frac{1}{\tan(\theta_0 - \theta_t)}\right]. \tag{6}$$

For $\theta_o \geqq 90°$, the shortest straight tunnel path runs along the gate oxide. For $\theta_o \geqq 90°$ and $R_1 \geqq R_2$, the length of this tunnel path

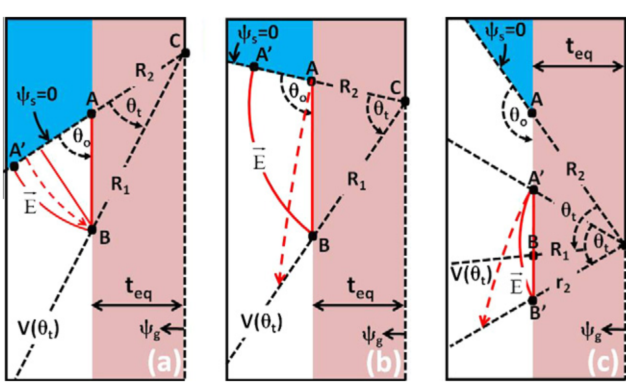

Fig. 2. Schematic view of the potential profile of a TFET with a junction angle θ_o illustrating the shortest straight tunnel paths (solid, (a and b): ending in B or (c): ending in B′), the shortest circular tunnel paths along the electric field (solid, starting in A′), the shortest tunnel paths along the oxide–channel interface (solid, (a and b): line $\overline{AB}$ or (c): line $\overline{A'B'}$) and the shortest tunnel paths along the classical particle trajectories with zero initial velocity (dashed arrow (a): ending in B, (b): starting in A, or (c): starting in A') (a): $\theta_o < 90°$; (b): $R_1 > R_2$ and $\theta_o > 90°$; (c): $R_1 < R_2$. Note that $R_1 = \overline{BC}, R_2 = \overline{AC}$, and $r_2 = \overline{A'C} = \overline{B'C}$. $V(\theta_t) = E_g/q$ is with respect to $\psi_s = 0$. Note that blue, red and white regions are indicating source, gate oxide and channel regions, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)