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Impact of source-to-drain tunnelling on the scalability of arbitrary oriented alternative channel material nMOSFETs

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ABSTRACT

In this work, the scalability of alternative channel material double gate nano nMOSFETs has been investigated by the mean of semi-analytical models of I_{on}/I_{off} currents, accounting for quantum capacitance degradation, short channel effects, band-to-band and source-to-drain tunnelling in arbitrary substrate and channel direction.

Contrary to most of the previous study neglecting source-to-drain tunnelling, it has been found that for devices with physical gate length below 13 nm (as required in the 22 and 16 nm nodes), this mechanism significantly penalises the I_{on}/I_{off} trade off of small effective masses channel materials like Ge or GaAs, much more than in the case of Si and biaxially strained Si (s-Si). In addition, only strained Si-MOSFETs has been found to meet the performance expectation of the International Technology Roadmap of Semiconductor for the 22 nm and 16 nm technological nodes.

1. Introduction

Alternative channel materials, such as germanium and relevant III–V like GaAs or InAs, have recently been widely studied, both experimentally [1–14] and theoretically [15–26], as possible technological boosters needed to meet the performance expectations of the last nodes of the ITRS. Attractive for their high bulk material mobilities (3900 $cm^2/V/s$ for electron in Ge, 8500 $cm^2/V/s$ in GaAs versus 1500 $cm^2/V/s$ in Si), they also appear to be promising in the quasi-ballistic transport regime [27]. Indeed, high mobilities are expected to lead to weaker scattering in the channel [28], beneficial for the on-state current. Moreover, the small effective masses associated with these high mobility materials (0.067 m_0 and 0.023 m_0 for the Γ valley of GaAs and InAs respectively and 0.08 m_0 for the transverse mass of Λ valley in Ge) increase the injection velocity at the virtual source, as shown in [18,19,23–26], which also contributes to quasi-ballistic drain current enhancement.

However, even though promising, these alternative materials may also suffer from several physical drawbacks. First of all, as pointed out in [23,29], the small effective masses of these materials could induce a severe quantum capacitance degradation, phenomenon also called “density of state (DOS) bottleneck”, detrimental for the on-state current. Moreover, due to their higher dielectric constants, short channel effects (SCE) are also expected to be enhanced [19,30], which could lead to possible higher off-state current. Other sources of subthreshold current degradations are band-to-band tunnelling (BBT) and direct source-to-drain tunnelling (SDT) (Fig. 1) in nano-channels. BBT has been extensively studied [15,17,19,31,43] and identified as one possible scaling limit for alternative channel material devices, (especially in direct or small indirect band gaps materials). However, to our knowledge, SDT, while recognised as one of the major source of leakage currents in Si-MOSFETs device with channel length below the 10 nm range [32,33], has only been included in a limited number of works on alternative channel materials [15,17,20], where only gate length longer than 10 nm were considered. At last, its impact on the scalability of these devices into the 22 and 16 nm nodes has not been systematically estimated in alternative channel material transistors.

In addition, the investigation of the advantages of alternative channel materials must be associated with the determination of the optimum channel orientation (versus substrate orientation), as already shown in [15,16,18,23,26] in the case of germanium, and in [26] for various III–V compound materials.

In this work, a semi-analytical model of the ballistic drain current, accounting for quantum capacitance degradation, SCEs and more importantly SDT in any possible channel orientation has been derived and used to investigate the possible performance enhancement and scalability of Ge and GaAs double gate MOSFETs (DGFETs) compared to Si and s-Si references. Following [15–26], transport has been assumed full ballistic in this work, as a good

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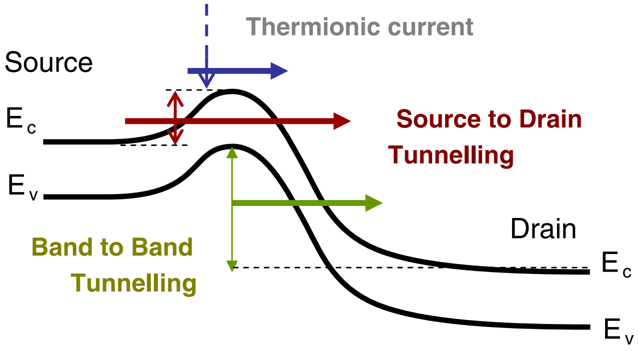

Fig. 1. Sketch of the three different source of leakage considered in this work. Thermionic current consists in electrons moving from the source to the drain with an energy higher than the barrier (conventional leakage); source-to-drain tunnelling current consists in electrons from the conduction band of the source tunnelling into the drain through the channel potential energy barrier; band-to-band tunnelling current consists in electrons from the valance band tunnelling through the gap to the drain.

approximation of the performances upper limits in ultra scaled nMOSFETs.

Details of the model derivation are given in the first section. The channel orientation optimisation in presence of non-negligible SDT is presented in the second section. Finally, the channel materials along the 32 nm, 22 nm and 16 nm nodes of the 2006 updated edition HP 2006 ITRS have been compared in the last section.

2. Model description

In the full ballistic regime, the equation of a current flowing between two 2D electron gas reservoirs in equilibrium separated by energy barrier can be written on the basis of the Landauer formula

$$I_{\rm d}/W = q\sum_{v}\sum_{n}\int_{-\infty}^{\infty}\int_{0}^{+\infty}\frac{1}{\hbar}\frac{\partial E(\vec{k})}{\partial k_x}T(E_x)[f(E(\vec{k}),E_{\rm f_S}) - f(E(\vec{k}),E_{\rm f_D})]\frac{{\rm d}k_x{\rm d}k_y}{2\pi^2} \tag{1}$$

where q is the elementary charge, $\hbar$ the reduced Plank constant, $E(\vec{k})$ the energy of a wave vector electron with a with k_x and k_y its device Cartesian coordinates (x being the source–drain direction), $E_{\rm f_S}$ and $E_{\rm f_D}$ respectively the source and drain Fermi levels, E_x the energy of the electron in the x direction, $T(E_x)$ the quantum transparency of the energy barrier between the two reservoirs, and $f(E(\vec{k}),E_{\rm f_{S/D}})$ the Fermi–Dirac supply function

$$f(E(\vec{k}),E_{\rm f_{S/D}}) = \left[1+\exp\left(\frac{E(\vec{k})-E_{\rm f_{S/D}}}{k_{\rm b}T}\right)\right]^{-1} \tag{2}$$

where $k_{\rm b}$ is the Bolztmann constant and T the temperature.

The double integrals sum the contributions from all electrons whose velocities are positive in the x direction and arbitrary in the y one. Finally, the contributions from all subbands of all valleys of the 2D quantized electron gas are summed over the n (subband) and v (valley) indices.

Eq. (1) is valid both in above threshold and subthreshold regimes, and takes into account the source-to-drain tunnelling contribution to the off-state and on-state current. It can be solved though time consuming self-consistent two dimensional Poisson–Schrödinger calculations [34] or by non equilibrium Green function (NEGF) simulations [35]. In this work, for sake of simplicity and computational efficiency, needed to analyse the various technological options investigated in this work, a semi-analytical model has been derived from the simplification of Eq. (1) either in on-state or the off-state regimes.

In the on-state regime, following the approach of Natori [36] and Assad et al. [37], the electron injection has been calculated at the top of the energy barrier, the so-called virtual source, assuming a transparency equal to 1 (semiclassical approximation). Consequently, the small contribution of SDT to the on-current has been neglected. This approach, commonly used to estimate ballistic on current [18,21–26], avoids the 2D self-consistent calculation of the charge along the channel, assuming that the charge at the virtual source is fully controlled by the gate. The charge at the virtual source and the subband energy levels however need to be self-consistently solved by one dimensional Poisson–Schrödinger calculation.

The Natori formula, initially derived in conventional (100)/[100] Si device, has been generalized [23,26], in order to take into account all the relevant conduction band minima, and to account for substrate and channel orientation, using the recasting procedure of Stern [38]:

$$\frac{I_{\rm d}(\alpha)}{W} = q\frac{\sqrt{2}\cdot(k_{\rm b}T)^{3/2}}{\pi^2\hbar^2}\sum_{v}\left(\sqrt{m^{v}_{\rm trans}(\alpha)}\right)\sum_{n}\left[F_{1/2}\left(\frac{E_{\rm f_S}-E^{v}_{n}}{k_{\rm b}T}\right) - F_{1/2}\left(\frac{E_{\rm f_S}-E^{v}_{n}-qV_{\rm d}}{k_{\rm b}}T\right)\right] \tag{3}$$

with $$\sqrt{m^{v}_{\rm trans}(\alpha)} = \sqrt{m^{v}_{1}}\cos(\alpha-\alpha^{v}_{0}) + \sqrt{m^{v}_{1}}\sin(\alpha-\alpha^{v}_{0}) \tag{4}$$

m_1 and m_2 are the in-plane Stern masses as described in [38]. α_0 is a reference angle used to align all ellipsoids with a common crystalline direction (see [26] for more details).

In the off-state regime, the transparency of the energy barrier can not be simply assumed equal to 1 if source-to-drain tunnelling is taken into account. However, in the off-state regime, the computation of the energy barrier (from electrostatics) is not self-consistent, and an analytical approach can be used.

To this aim, the subthreshold energy barrier has been modelled using the approach proposed in [30], which accounts for short channel effects. This model has been fatherly improved by considering the quantum depletion in the source and drain due to wave function reflection on the barrier by the mean of quantum Gaussian convolution [39]. As shown in Fig. 2, the resulting energy barrier has been found in very good agreement with the one obtained with the NEGF simulator NanoMOS [40], without introducing any fitting parameter. The transparency of the barrier has been then calculated using the scattering matrix formalism [41], which also compares very well with the transparency calculated by NanoMOS (Fig. 3).

To properly account for the dependence of the subthreshold current with the device orientation, Eq. (1) must be integrated in the polar coordinate system, and the boundaries of the integral must be expressed in function of the source–drain direction. Details of application of (1) in arbitrary oriented substrate are given in Appendix A, leading to the following expression:

$$I_{\rm d}(\alpha)/W = \frac{2q}{\hbar^2\pi^2}\sum_{\rm valley}\sqrt{m_1 m_2}\sum_{n}\int_{0}^{\infty}\rho f(\rho^2) \times\int_{\alpha-\pi/2}^{\alpha+\pi/2}V(\alpha,\rho,\theta)T(E_x(\alpha,\rho,\theta)){\rm d}\theta\,{\rm d}\rho \tag{5}$$

where V is the velocity of an arbitrary electron in the x direction and E_x the corresponding kinetic energy. It can be seen on Fig. 4 that the subthreshold drain current obtained by Eq. (7) and the one obtained by NanoMOS for two different silicon double gate MOSFET geometries are also in very good agreement.

Finally, band-to-band tunnelling (BBT) leakage mechanism has also been considered using the phenomenological model of Hurkx