Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 42-43

B-2-1 (Invited)

Technology Oriented Analytical Models of MOSFETs in the Quasi Ballistic Regime

R. Clerc[1], Q. Rafhay[1], M. Ferrier[1], P. Palestri[2], G. Ghibaudo[1], L. Selmi[2]

[1]IMEP, Minatec-INPG, 3 parvis Louis Néel, Grenoble, France
[2]DIEGM, University of Udine, Via delle Scienze 208, Udine, Italy

1. Introduction

The Quasi Ballistic (QB) regime of transport has been considered by the ITRS roadmap as a possible "technological booster" for MOSFET [1], leading to a level of current in the ON state significantly higher than expected using the conventional drift diffusion theory (Fig. 1). The accurate evaluation of the corresponding "ballistic enhancement factor" versus device characteristic can only be addressed by mean of highly sophisticated simulations based on Multi Subband Monte Carlo (MSMC) (i.e MC accounting for degeneracy and transverse quantum confinement [2, 3]), or full quantum (accounting for scattering) approaches [4]. In the meantime, technology oriented analytical models are also needed to explain and summarize time consuming numerical results, and allow a qualitative evaluation of device performances in the quasi ballistic regime versus device architecture (dimension, doping etc). The aim of this paper is to review the state of the art in this area.

2. Analytical modeling of the ballistic limit

The concept of ballistic limit in MOSFET, i.e. regime of transport limited by the injection of carrier at the entrance of the channel (referred as Virtual Source, VS) rather than by the channel itself, has been introduced first by Natori [5]. This approach, assuming negligible short channel effects, allows a simple quasi analytical evaluation of ballistic performances (I_{on} current, and injection velocity V_{inj} i.e. the ratio I_{on} / Q_i, where Q_i is the inversion charge at the virtual source), accounting for quantum confinement and degeneracy (Pauli's exclusion principle), in relatively good agreement with ballistic MSMC simulations (Fig. 2). Initially introduced for Si (100) bulk and SOI devices, this approach has been generalized to different architectures, with or without strain (Fig. 3 and ref. [6-7]) , and to arbitrary oriented alternative channel materials, such as Ge or GaAs (see Fig. 4, and ref. [6-10]). It also captures the impact of VS density of state (DOS) reduction due to enhanced quantum confinement effects on ballistic performances, which leads to an improvement of injection velocity as well as a degradation of quantum capacitance effects [10]. Negligible in Si, (see Fig. 5), the reduction of quantum capacitance in extremely low DOS materials significantly affects ballistic currents [10].

3. Scattering in the quasi ballistic regime

However, MC simulations [11-13] have shown that the limited amount of scattering occurring even in nanometer devices (referred as Quasi Ballistic QB devices) also significantly impacts performances. Lundstrom et. al. have generalized the Natori model introducing the concept of backscattering coefficient r [14] (namely the ratio between the flux of carrier re-injected to the source by scattering events divided by the flux of injected carriers). At low source - drain voltage, assuming a constant mean free path λ, it can be demonstrated [14-15] that $r = L / (L + \lambda)$. In high field conditions, arguing that after a critical distance L_{kT} (L_{kT} being the distance needed by the potential energy to drop from the entrance of the channel by a quantity kT), scattering events would not be able to re-inject carrier into the source (because of the source to drain electric field attraction), the previous formula has been empirically extended by substituting the channel length L with the critical distance L_{kT}, leading to $r = L_{kT} / (L_{kT} + \lambda)$ (Fig. 6). Finally, by defining the mean free path as $\lambda = 2\ \mu\ (k\ T/e) / v_{th}$ (where μ is the low field mobility in long channel devices), the obtained formulas (in high field and low field conditions) are consistent with their ballisitic (when L or $L_{kT} << \lambda$) and Drift Diffusion (when L or $L_{kT} >> \lambda$) counterparts. This also demonstrates that the long channel mobility is still a relevant figure of merit of QB devices. The validity of these formula have been investigated in details by the mean of MC simulations, showing that 1/ the expressions for r and λ are qualitatively correct in low field condition [16], 2/ in high field condition, r can be fitted by L_{kT} / ($L_{kT} + \lambda_F$), but using λ_F as a fitting parameter [12,16], 3/ λ_F is indeed proportional to the mobility, but with a roughly 50 % lower slope (Fig. 7)[16]. A deeper look on the theoretical basis of the kT layer concept and on many MC simulations have provided an explanation for this discrepancy, showing that the kT layer concept is only valid when the flux of backscattered carriers follows a thermal Maxwellian distribution [17], and that the non equilibrium nature of this flux is responsible for the apparent reduction of λ_F [16]. Using a more suitable backscattered distribution function, an improved model can be obtained that better reproduces the backscattering coefficient (Fig. 8) and the velocity profiles (Fig. 9) extracted from MC. In conclusion, the Lundstrom theory, using a suitable set of L_{kT} and λ_F parameters can be used to investigate QB device performances, qualitatively explaining for instance the impact of biaxial strained Si channel [18] (see Fig. 10-11) or the observed degradation of performance in undoped devices, probably due to neutral defects [19] (see Fig. 12). However, improvements are needed, in particular to self consistently model velocity profiles along channel and variation of the kT layer versus bias.

Acknowledgments :
This work has been partially funded by the PULLNANO project (FP6, IST-026828-IP) and the French ANR project Modern.

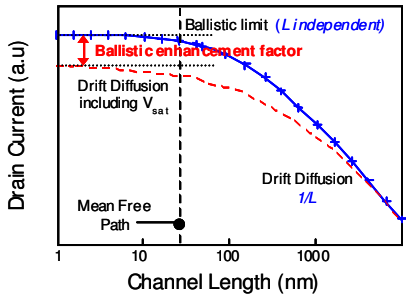

Fig 1 : Schematic MOSFET saturation drain current versus channel length, showing that both drift diffusion (including velocity saturation) and quasi ballistic model predict a L independent current at channel length shorter than the mean free path.

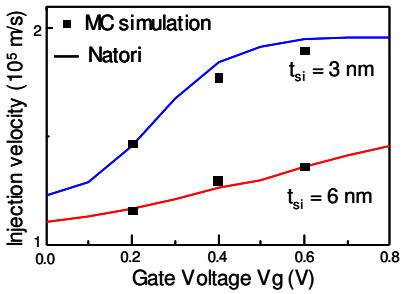

Fig. 2 : Injection velocity versus gate voltage in two undoped Double Gate (DG) nMOSFET with negligible short channel effects (t_{si} = 3 nm, L = 18 nm & t_{si} = 6 nm, L = 28 nm), computed according to the Natori model and extracted from MSMC simulations [7].

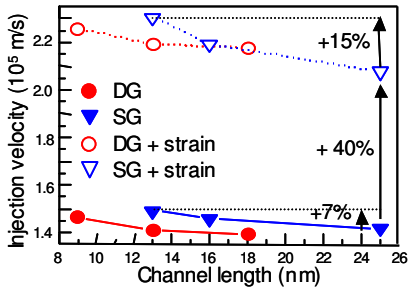

Fig. 3 : Evolution of the injection velocity versus scaling, in Single Gate (SG) and DG nMOSFETs. The reduction of the body thickness and of the buried oxide in the SG case) leads to minor improvements, while the biaxial strain (30 % of Ge in $Si_{1-x}Ge_x$ substrate) significantly improves injection velocity.

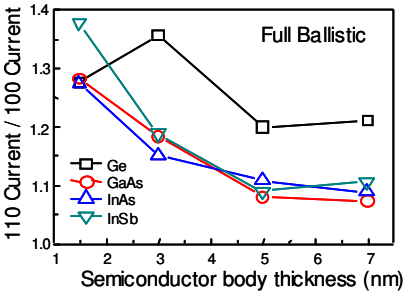

Fig. 4 : Ratio between the (anisotropic) ballistic current in 110 substrate (channel oriented in the best direction) and isotropic 100 substrate for GaAs-like materials and Ge nMOSFET using Natori model, showing that 110 substrates always give better current (comparison performed at same inversion charge, not necessarily same I_{off})

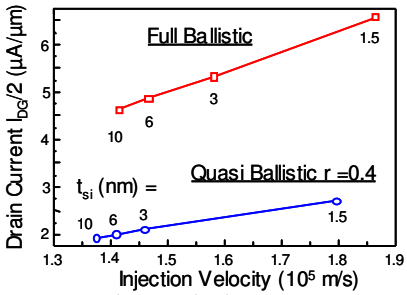

Fig. 5 : Sat. Drain current in Si DG nMOSFET (EOT=6Å, $Vg-V_T$=0.8V, V_d =1 V) versus injection velocity when drastically scaling the body thickness t_{si} according to Natori Lundstrom approach. Current is still proportional to V_{inj}, even if the reduction of t_{si} also enhances parasitic quantum capacitance effects. (series resistance enhancement of scattering in ultra thin body not included).

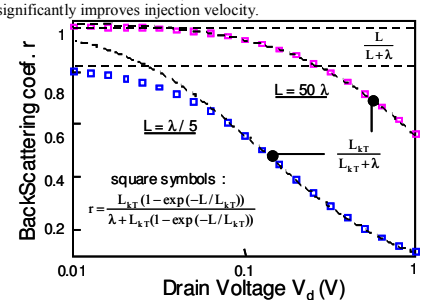

Fig. 6 : Backscattering coefficient r versus applied voltage in a linear (non self consistent) potential profile, according the ballistic drift diffusion theory proposed in [17], validating the empirical L / (L + λ) and L_{kT} / (L_{kT} + λ) formulas under the assumption of *thermal* backscattered flux of carriers.

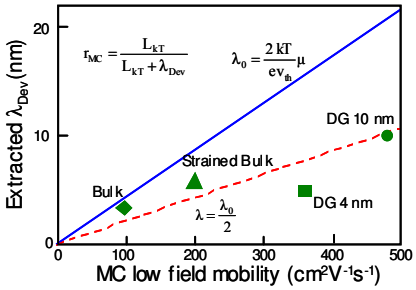

Fig. 7 : Mean Free Path λ_{Dev} extracted from MSMC simulations (by fitting the MSMC backscattering coefficient by r_{MC} = L_{kT} / (L_{kT} +λ_{Dev})) versus the low field mobility µ calculated by MSMC simulations on various devices. λ_{Dev} is still proportional to µ, but with a slope roughly a factor of 2 lower than expected from the Lundstrom theory [16].

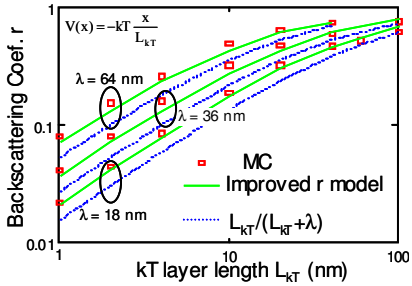

Fig. 8 : Backscattering coefficient r versus L_{kT} in a non self consistent linear potential profile, calculated according to the Lundstrom model (dot line), non degenerated MSMC simulations (symbol) and an improved semi analytical model, taking into account the non thermal nature of the backscattered flux.

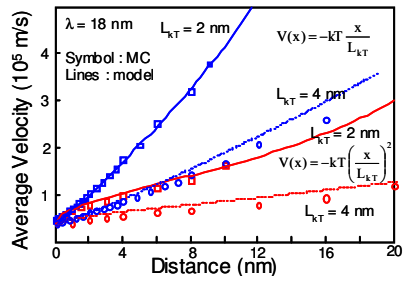

Fig. 9 : Average velocity versus distance in non self consistent linear or parabolic potential profile (for two kT layer lengths), calculated using non degenerated MSMC simulations (symbol) and the improved model of Fig. 8..

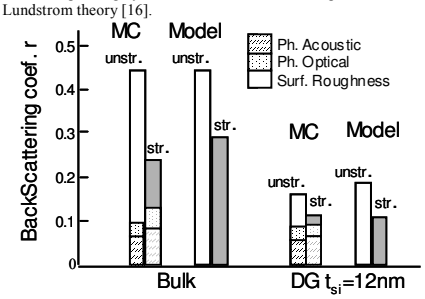

Fig. 10 : Comparison of backscattering coefficient r in Bulk and undoped DG devices (L = 25 nm) with and without biaxial strain (20 % of Ge in $Si_{1-x}Ge_x$ substrate ,see [18]) calculated with MSMC simulations and the simple Lundstrom formula using universal mobility including the ½ correction factor to λ suggested in [16] (see also Fig. 7).

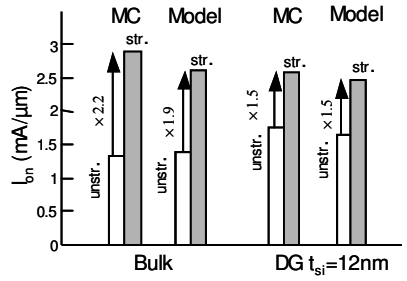

Fig. 11 : Comparison of I_{on} current in Bulk and undoped DG devices (L = 25 nm) with and without biaxial strain (20 % of Ge in $Si_{1-x}Ge_x$ substrate, see [18]) calculated with MSMC simulations and the simple Natori -Lundstrom model using universal mobility and the ½ correction factor to λ suggested in [16] (see also Fig. 7). The impact of strain, leading to r and Vinj improvements, is well captured by the model.

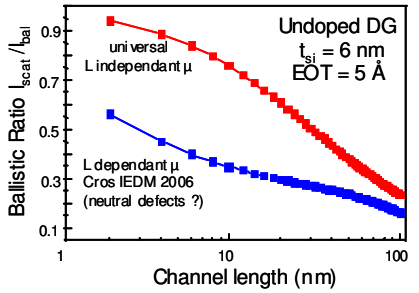

Fig. 12 : Prediction of ballistic ratio (I_{on} / I_{on} full ballistic) using the Lundstrom model in an undoped DG nMOSFET, using a constant mobility (universal) and accounting for the reduction of mobility versus channel length [19], possibly due to the negative impact of neutral defects generated by implantation.

References : [1] ITRS 2005 Public Home Page. [2] M. V. Fischetti et al., Phys. Rev. B 48 p. 2244 (1993), [3] L. Lucci et al., in Proc IEDM, 2005, p.617 [4] S. Datta, Superlatt. Microstruct. 28 p 253 (2000) [5] K. Natori, J. Appl. Phys., vol. 76 p. 4879 - 4890 (1994); [6] S. I. Takagi et. al. Solid State Elect., vol. 49, pp. 684–694, (2005); [7] M. Ferrier et al. Proc. SNW 2006, to appear in IEEE TNANO [8] S. I. Takagi, proc. VLSI symposium (2003) , [9] K. C. Saraswat et. al. in IEDM Techn. Digest, (2006); [10] M. De Michelis et. al. IEEE TED 54 p. 115 (2007). [11] S. Eminente et.al. IEEE TED 52 p. 2736 (2005).[12] P. Palestri et. al. IEEE TED 52 p. 2727 (2005). [13] J. S. Martin et. al. IEEE TED 51 p. 1148 (2004). [14] M. Lundstrom, et. al., IEEE TED, 49 p. 133 - 141 (2002) ; [15] M. Lundstrom « Fundamental of Carrier Transport » Cambridge (2000) [16] P. Palestri, et. al. in proc IEDM, p.945 (2006) [17] R. Clerc et.al., IEEE TED 53, p 1634 – 1640 (2006); [18] D. Ponton et.al. Proc. Essderc p. 166 (2006); [19] A. Cros et. al., proc. IEDM, p. 663, (2006).