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On the accuracy of current TCAD hot carrier injection models in nanoscale devices

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ABSTRACT

In this work, the hot electron injection models presently available for technology support have been investigated within the context of the development of advanced embedded non-volatile memories. The distribution functions obtained by these models (namely the Fiegna Model – FM [1], the Lucky Electron Model – LEM [2] and the recently implemented Spherical Harmonics Expansion of the Boltzman's Transport Equation – SHE [3]), have been systematically compared to rigorous Monte Carlo (MC) results [4], both in homogeneous and device conditions. Gate-to-drain current ratio and gate current density simulation has also been benchmarked in device simulations.

Results indicate that local models such as FM, can partially capture the channel hot electron injection, at the price of model parameter adjustments. Moreover, at least in the device and field condition considered in this work, an overall better agreement with MC simulations has been obtained using the 1st order SHE, even without any particular fitting procedure.

Extending the results presented in [3] by exploring shorter gate lengths and addressing the floating gate voltage dependence of the gate current, this work shows that the SHE method could contribute to bridge the gap between the rigorous but time consuming MC method and less rigorous but suitable TCAD local models.

1. Introduction

In the context of advanced NOR Non-Volatile Memories (NVM) development, the TCAD community has been brought recently to re-investigate the issue of predictive channel hot electron injection modelling. Many approaches have been developed throughout the years to tackle this difficult task. One of the first attempts to explain the origin of hot electron current in MOSFET has been presented by C. Hu's group in the late 1970s [5], who based their work on Shockley's lucky electron concept [6]. However, their approach, referred as Lucky Electron Models (LEM) [2] treats phonon and impact ionization scattering in a somewhat oversimplified way. Monte Carlo (MC) simulators have been hence developed during the mid 1980s [7,8] and have succeeded a decade later to more rigorously capture the physics of hot electron generation and injection [9–11]. Despite its recognized accuracy to account for phonon, coulomb and impact ionization scattering mechanisms, MC simulations can not be daily used to support technological development due to their computational burden. Therefore, new TCAD suitable models, such as the Fiegna model (FM) [1,12], have been derived based on the results obtained by MC simulation. However, as discussed in [9], such approximated approaches can only partially reproduce channel hot electron injection preventing the TCAD community from having an accurate technology prediction. During the 90s, the direct solution of the Boltzmann Transport Equation (BTE) through Spherical Harmonic Expansion has been investigated [13–15] as a possible solution to this dilemma. Recently a 1st order Spherical Harmonic Expansion (SHE) solver of the BTE has been implemented in a commercial TCAD simulator [3,16]. According to [3], this model is expected to be rigorous and suitable for TCAD application thanks to its fast execution. But some relevant comparisons with MC simulation are still needed as only relatively long devices have been simulated in [3]. In addition, gate current comparisons with Monte Carlo simulation have not been shown yet for NVM devices.

In this context, the aim of this paper is therefore to benchmark these different TCAD models (LEM, FM and SHE) and to assess their ability to accurately model hot electron injection in advanced

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device architectures. In this work, state of the art Full-Band Monte Carlo [4] simulation will be used as reference. In Section 2, the different modelling approaches will be briefly reviewed. The channel hot electron distribution functions will then be investigated in the framework of homogeneous transport in a Section 3. Finally, the Section 4 will be dedicated to inhomogeneous transport in advanced eNVM, pointing out the strengths and weaknesses of the different approaches.

2. Models' description

As underlined in [9], the accurate simulation of channel hot electron injection is a complex task. To be considered as a reference in the modelling comparison, the Monte Carlo simulator used in this work [4] to benchmark the TCAD models fulfils the requirements highlighted in [9], i.e. it accounts for the full-band structure of silicon, for full band phonon scatterings, scatterings with ionized impurities and impact ionization scatterings. Such a setup has also been used in previous works for electron and hole injection on different cell architectures [4,17] and successfully compared to experimental data for carrier injection. Moreover, the electron–electron interaction and scatterings in the tunnel oxide have been neglected in this work since we consider drain to source voltage large enough to provide the high energy electron tail and we consider floating gate voltages at which scattering in the oxide is expected to weakly influence the results [11]. This ensures also a fair comparison between models, since none of the TCAD model presently includes these mechanisms. In the MC simulations, the gate current has been calculated as:

$$I_g = \sum_i \frac{q w_i P(\varepsilon_\perp^i, x)}{\Delta t \cdot W} \tag{1}$$

where i represents the particles hitting the interface at the x position during the time interval Δt with a statistical weight w_i. $P(\varepsilon_\perp^i, x)$ is the tunnelling probability of a given particle hitting the interface with a given perpendicular energy $\varepsilon_\perp$. The current is then normalized to the width W. Since defining a perpendicular energy in a full-band structure is not obvious, once a particle hits the interface, we estimate the perpendicular energy by conserving the parallel momentum [9]:

$$\varepsilon_\perp = \varepsilon_{tot} - \frac{\hbar^2 k_\parallel}{2 m_{ins}} \tag{2}$$

In this expression $m_{ins} = 0.5\ m_0$ is the electronic mass inside the oxide, $k_\parallel$ is the parallel wavevector referred to the Γ point and ε_{tot} is the particle's total energy with respect to the nearest conduction band minimum. Furthermore, barrier lowering due to image force has been accounted for.

All TCAD models operate as post processing steps after transport simulation carried out in the Drift Diffusion or the Hydrodynamic approximations. In addition to the Non-Self Consistent (NSC) MC simulations [18], which are directly comparable to the present TCAD models, Self Consistent (SC) MC results are also presented in the main figures of the article.

The LEM is based on a probabilistic view of the channel hot electron injection (see [2]) and the implicit distribution function is given by:

$$f(\varepsilon)_{LEM} = A \cdot \exp(-\varepsilon / qE\lambda) \tag{3}$$

where A is a normalization constant, ε the carrier energy, E the local field, q the electron charge and λ the constant mean free path of the electron, which value has been discussed in [2]. Eq. (3) therefore corresponds to a heated Maxwellian distribution function.

On the contrary, the Fiegna model is derived from the BTE, assuming homogeneous conditions [1] and a non-parabolic dispersion relation [12]. The distribution function of this model is expressed as:

$$f(\varepsilon)_{Fiegna} = B \cdot \exp(-\kappa \cdot \varepsilon^3 / E^{1.5}) \tag{4}$$

with B a normalization constant and κ a fitting parameter.

The SHE method implemented in [16] is analytically derived from the BTE, obtained by projecting the distribution function on a spherical harmonics basis and taking into account only the 0th and the 1st order terms. This formalism transforms the initial integro-differential Boltzmann Transport equation into a 2nd order differential equation. The model, based on the results in [19], uses a single isotropic non-parabolic band-structure and includes acoustic and optical phonon scatterings, as well as impact ionization scattering, which have been adjusted to reproduce the Ning's experiment [20].

3. Results: homogeneous case

As exposed in the previous section, both LEM and FM have been derived assuming homogeneous conditions, i.e. for constant electric field and considering carrier transport as independent of spatial variable [1,5]. The ability of the different models to reproduce hot carrier generation is at first evaluated in this context. Fig. 1 compares the distribution functions obtained with the LEM, FM, SHE and Full-Band MC, for different values of the electric field.

Fig. 1 confirms that the heated Maxwellian distribution function (Eq. (3)), consequence of the constant mean free path assumption [2], cannot reproduce the MC simulations in the range of electric fields and energies used for hot electron injection.

As shown in Fig. 1, the FM distribution functions, after adjusting the model parameter κ, much better agree with the MC results. The best agreement has been reached for $\kappa = 5 \times 10^7\ \mathrm{m^{3/2}\ eV^{-3/2}}$.

The distribution function obtained with the SHE is in good agreement with the MC results for fields up to $10^5\ \mathrm{V\,cm^{-1}}$, confirming the results obtained by [3]. However, it can be noticed that this agreement is somewhat worsening for higher electric fields. The plausible causes for this discrepancy are: the band-structure, the scattering mechanisms and the 1st order approximation of the SHE model. Fig. 2 shows the full-band and the non-parabolic band-structure used to investigate the band-structure effect on such discrepancy. The non-parabolic band-structure includes the

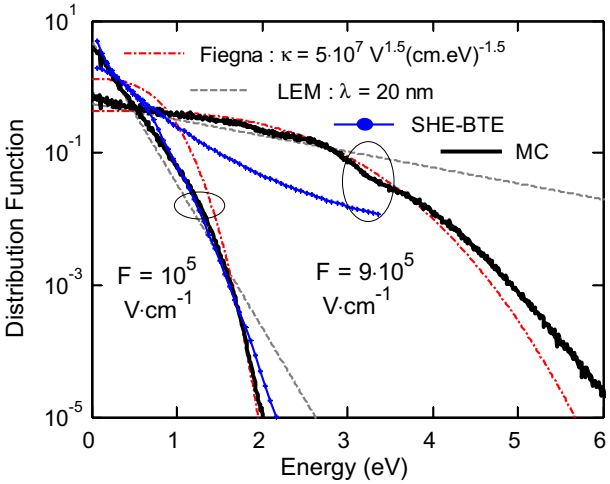

Fig. 1. Distribution functions simulated under constant electric field with the Monte Carlo method (MC), the Spherical Harmonics Expansion of the Boltzmann Transport Equation method (SHE–BTE), the Lucky Electron Model (LEM) and the Fiegna model. Curves have been normalized to give the same carrier concentration.