Historical perspective and recent developments of hot-carrier generation modeling for device analysis

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***Abstract*—The paper presents an historical perspective of the efforts devoted in the past years to achieve efficient but increasingly accurate modeling of hot carrier generation in MOS devices. In addition, new modeling problems raised by recent experiments, and related to the effects of power supply and geometry down-scaling will be discussed.**

I. Introduction

The control and modeling of hot carriers, defined as carriers which attain substantial kinetic energy in excess of the average thermal energy, has been one of the most challenging tasks posed by MOSFET scaling, mainly because of the strict reliability constraints posed by the presence of energetic carriers, and by the growing importance of non-volatile memories, whose programming mechanism is essentially based on electron injection in the floating gate of a MOS structure.

The difficulty of this task derives from the strongly non-equilibrium nature of hot carrier transport, which makes simple equilibrium or quasi-equilibrium models not physically sound and often oversimplistic.

The most suitable modeling approach for this problem is the solution of the semiclassical Boltzmann transport equation (BTE). However, practical solutions of the BTE were not available in the seventies when hot carriers started to become a constant reliability burden in technology development [1] and the first hot-carrier based non-volatile memories were proposed [2].

In the following years, in spite of these "a priori" limitations, simple models have been widely popular and sometimes provided satisfactory practical results. A whole hierarchy of models of increasing complexity and accuracy has been developed since then. The fundamental aspects of the most commonly adopted modeling approaches will be reviewed in the following sections.

II. Lucky Electron Model

The simplest model to analyze hot carrier effects in devices, the lucky electron model (LEM) [3]–[6], evaluates the probability to attain a given kinetic energy E_c through a single ballistic flight in a constant field. Basically, the LEM suffers two major limitations: a) it relates hot carrier effects (HCE) to the local field (F_L), thus neglecting the space and time lag of carriers in reaching local equilibrium with the field; b) since the potential energy is the only source of energy available to the carriers, the maximum attainable kinetic energy is limited to qV_{TOT} where V_{TOT} is the total voltage drop experienced by the carriers. Therefore, contrary to experimental evidence (Fig.1 and [7]–[9]), the LEM predicts no HCE at voltages smaller than the threshold energy of the considered phenomenon [5], [6].

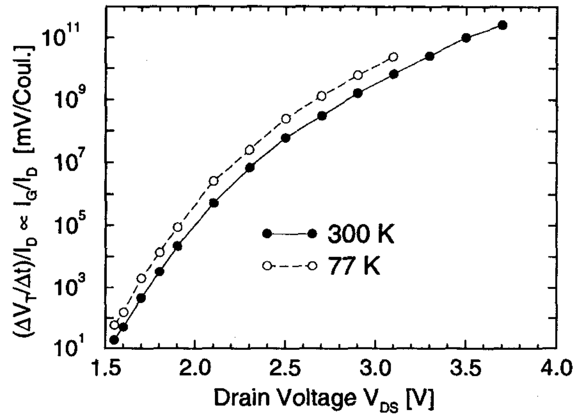

Fig. 1. Gate current of a typical floating gate MOSFET. Substantial I_G is observed even for $V_{DS} \ll 3V \approx \Phi_B/q$.

III. Higher Order Models

Attempts to overcome these limitations can be classified as: 1) "non-local" LEMs; 2) effective temperature models (ETM). Non-local LEMs [10], [11] replace F_L with "non-local" quantities such as the potential drop along the current flowlines [10] or a suitable effective electric field (F_{EFF}) [11]. ETMs assume quasi-equilibrium Maxwellian distributions ($f(E)$) whose effective temperature (T_e) is a function of F_L [8]. In their simplest form, LEM and ETM predict the following relationships between substrate (I_B) and gate (I_G) currents:

$$\begin{aligned} I_B &\propto I_D \exp(-\Phi_I/E^*), \\ I_G &\propto B(F_{OX}) I_D \exp(-\Phi_B/E^*)\ , \\ I_G/I_D &\propto (I_B/I_D)^{\Phi_B/\Phi_I}\ ; \end{aligned} \quad (1)$$

where $B(F_{OX})$ models the collecting efficiency of the gate, $E^* = q\lambda F_L$ for LEM, $E^* = k_B T_e$ for ETM, and Φ_I, Φ_B are the impact ionization and injection thresholds, respectively. It is interesting to notice that, as shown in Fig.2,

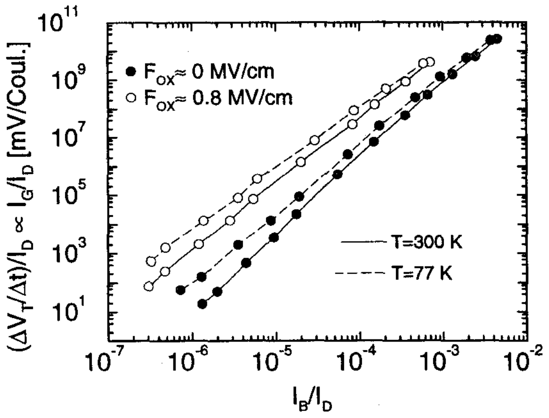

Fig. 2. Correlation between I_G and I_B at low V_{DS} (from 1.55 to 3.5 V). The slope of the curves ($\approx \Phi_B/\Phi_I$ according to LEMs) is approximately 2.5. $V_{SB} = 0$.

the correlation expressed by (1) holds even in up-to-date technologies down to V_{DS} much smaller than Φ_B/q and Φ_I/q so long as $V_{SB} = 0$. [8], [9]).

The linearity of the curves in Fig.2 points out that I_B and I_G are driven by exponential dependencies on a common source (the channel electron distribution function) and that the ratio between the average energies of the distributions of impact ionizing and of injected carriers remains very similar to Φ_B/Φ_I down to low V_{DS}. In addition the high energy tail of the carrier distribution appears to be effectively populated even at low V_{DS}, so that no dramatic reduction of HCE is observed when V_{DS} becomes smaller than the threshold energy [8], [9]. As already recognized in [12], these observations question the validity of the classic LEM [3]–[5] in the low-voltage regime.

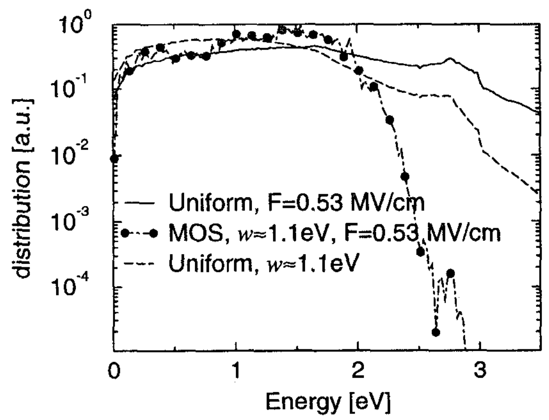

Fig. 3. Solid line: uniform field $f(E)$, $F = 0.53MV/cm$. Dashed line: uniform field $f(E)$ featuring $w \approx 1.1eV$ Dash-Dotted line: $f(E)$ at a point along the channel of a $0.2\mu m$ MOSFET featuring $w \approx 1.1eV$ and $F = 0.53MV/cm$. MC model of [13].

Further model improvements have been pursued either solving simplified forms of the BTE [15], or deriving simplified analytic expressions of non-Maxwellian distributions in terms of a limited set of process or device dependent parameters and of suitable non-local quantities

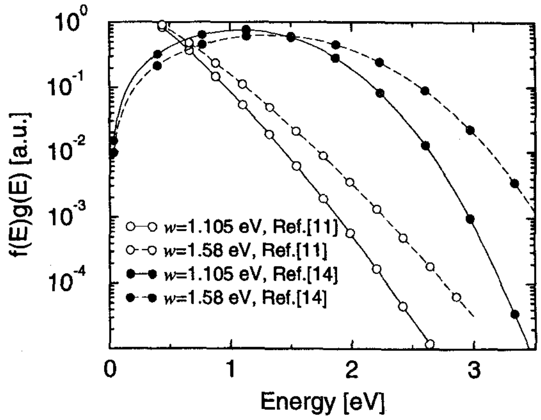

Fig. 4. Analytic carrier distributions corresponding to the same w according to the models of [11] and [14]. Different approximations in computing w result in much different curves even if both models provide good agreement with a wide set of experiments. Notice that w denotes the average carrier energy in the balance equation, but does not necessarily coincide with the average energy of the analytic distribution shown in the figure.

(average energy, w, effective field, F_{EFF}) computed integrating simple one-dimensional energy balance equations along the current flowlines [16], [17]. These models have been of considerable practical relevance in analyzing efficiently the engineering trade-offs encountered in device development [14], [18]. However, they are limited by the imposed "local" relationship between the shape of $f(E)$ and w (or F_{EFF}), thus partly overlooking the high sensitivity of the distribution tail to the actual potential profile (Fig.3). In addition, the different approximations and assumptions made in the analytical derivation of $f(E)$ and in computing w (F_{EFF}) result in distributions capable to reproduce macroscopic quantities such as I_B and I_G, but hardly comparable with each other for the purpose of a deeper understanding of high energy transport (Fig.4).

IV. New Problems

The current reduction of supply voltages and scaling of physical dimensions demands a detailed evaluation of the microscopic energy-gain mechanisms responsible of the substantial HCE observed at low V_{DS}. Obviously, this task can only be accomplished through the exact solution of the BTE, possibly via a spherical harmonics expansion of the distribution function [19], scattering matrix approaches [20], cellular automata techniques [21], or via the Monte Carlo method [22].

MC simulations, although still suffering of large CPU requirements and lack of parameters confidence have made formidable progress since the first attempts [24]. Compared to traditional approaches, Monte Carlo has demonstrated superior capabilities not as much in reproducing experimental results, but in providing a sound physical basis to attempt explanations of new phenomena [25], [26] and to steer the development of advanced device concepts. In addition, the comparison of simula-

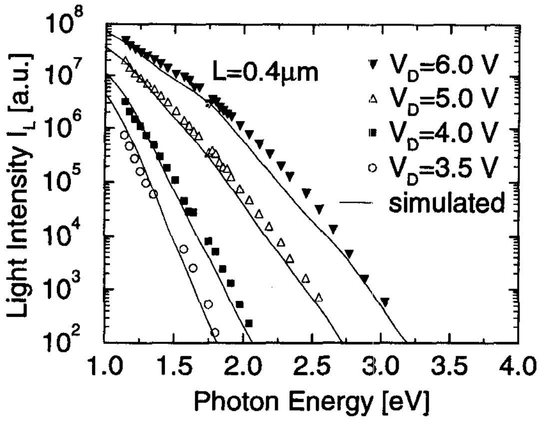

Fig. 5. Hot carrier induced photon spectra can provide detailed information on carrier distributions in semiconductor devices for investigation and verification purposes. As an example, the figure shows a comparison of measured and Monte Carlo simulated hot-carrier induced photon spectra [23].

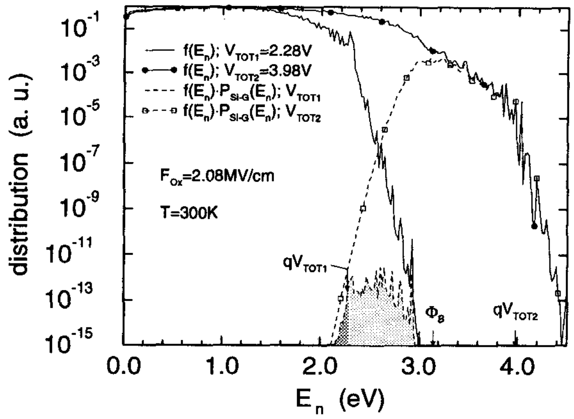

Fig. 7. Simulated distribution of carriers impinging on the interface (solid lines) and of carriers injected through the interface (dashed lines) for device A in Fig.6. The contribution of the thermal tail of the distribution ($E > qV_{TOT}$) to injection at low V_{TOT} is evidenced by the light filled area. The contribution to the injected gate current of carriers belonging to the tail can explain the bias and temperature dependence of P_{JN} shown in Fig.6.

tions with wide sets of experimental data sensitive to the details of carrier distributions at high energy (Fig.5) and the efforts made to compare model implementations [27] have clarified the consequences of different modeling approaches. In this way a significant reduction of the initial spread in fundamental parameters such as scattering rates and relaxation times has been achieved [11], [28].

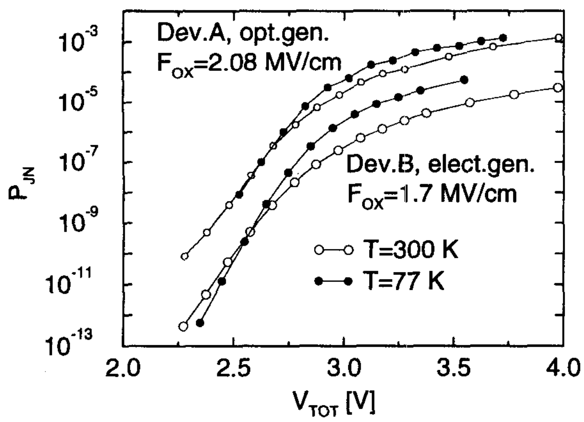

Fig. 6. Injection probability as a function of accelerating voltage in homogeneous injection experiments performed using different mechanisms for the generation of carriers in the substrate. As discussed in [25] the reversed temperature dependence at low V_{TOT} is consistent with the thermal tails observed in [29], [30].

As an example of recent applications, MC simulations predicted the presence of a tail in the distribution function with T_e equal to the lattice temperature at energies higher than the total voltage drop experienced by the carriers [29]. The actual existence of this tail, and its implications on low voltage HCE has been debated since then. Recent experiments [25] seem to confirm the presence of this tail in homogeneous injection conditions and its speculated origin based on net phonon absorption mechanisms [29], [30]. In particular, the abrupt transition between the field heated and the thermal tail parts of the distribution explains the observation of a sudden drop and a reversed temperature dependence of P_{JN} for $V_{TOT} < \Phi_B/q$ (Figs.6,7).

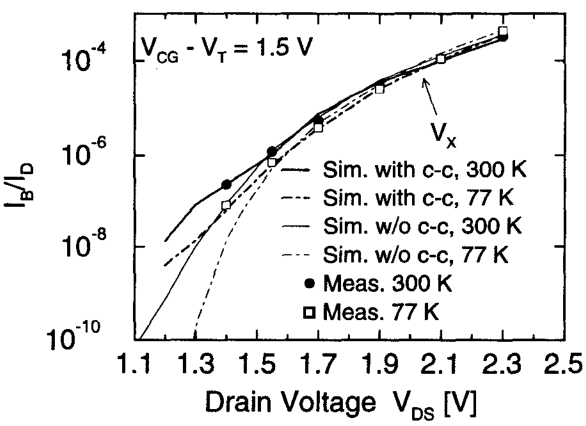

Fig. 8. Measured and simulated I_B of submicron floating gate MOSFETs. Including carrier-carrier scattering in the model accounts for the smooth decrease of I_B as V_{DS} decreases to Φ_I/q as compared to the abrupt decrease observed in Fig.6.

At the same time, comparing homogeneous results with MC analysis of I_B and I_G in MOS structures (Fig.8) strongly suggests that additional mechanisms, much more efficient than net phonon absorption, provide significant energy in excess of the potential drop to carriers at the drain end of the channel. [28], [30], [25], [13]. Carrier-carrier interaction and impact ionization feedback (IIF), appearing today as the most likely of these mechanisms [26], [28], [30], [13], require accurate models of complex interactions and statistical enhancement of extremely rare sequence of events, thus pushing even further the CPU requirements of physically based simulations. In particular, the enhancement of the gate current produced by the substrate voltage in deep submicrometer technologies so far attributed to the IIF mechanism, disrupts even the

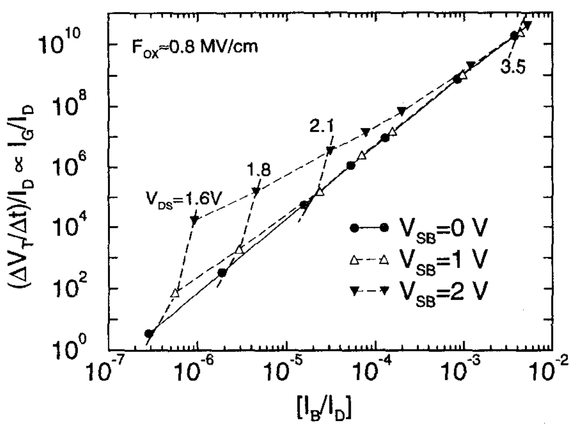

Fig. 9. I_G/I_D versus I_B/I_D correlation plot in devices exhibiting substantial enhancement of the gate currents possibly due to impact ionization feedback. For $V_{SB} > 0$ IIF disrupts the simple correlation typically observed in technologies down to approximately $0.5\mu m$ size (Fig.2).

simplest and most fundamental predictions of the LEM (eq.(1) and Fig.9).

The relative importance of these mechanisms, and the role of other, so far overlooked, microscopic effects (e.g. carrier-photon interactions) already appears very sensitive to technological details (doping levels, junction depths, device structure, bias, etc.) and this makes the modeling of carriers at energies exceeding the applied potential drop of key relevance for future MOSFETs operating at reduced supply.

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