Unification of Macroscopic Impact Ionization Models for Nonhomogeneous Fields

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Abstract

We have examined various macroscopic impact ionization models for semiconductor applications. Assumptions and range of validity of the local-field, local-temperature, lucky-electron and two-temperature models are revisited and compared. A unified view with asymptotic behaviors for these models in nonhomogeneous fields is established. Model characterization has been performed for MOSFETs versus experiments and nin diodes versus Monte Carlo calculations. Potential unified macroscopic impact ionization models are suggested.

I. Introduction

Modeling of impact ionization (II) in semiconductors is essential for many applications such as MOSFET and BJT reliability, and operations of hot carrier transistors and IMPATT diodes for communication circuits. In the literature, there are many proposed macroscopic II models, but their validity has been limited to applications with specific field profiles. With the current trends of optimizing device performance using detailed doping profiles and geometry (such that the electric field can not be well characterized by binary categories of gradual and abrupt), a unified view of the macroscopic II model with asymptotic correctness will be very useful for more predictive device modeling.

Although the detailed band structure, the distribution function in **k** space and detailed scattering rates will all affect the hot carrier population and hence II coefficients[1, 2], anisotropy in **k** space of II is usually not critical. For a reasonably accurate and widely applicable macroscopic II model, it is most important to account for [3, 4]: 1) the carrier energy-gaining process to estimate the hot carrier population [5], 2) the soft threshold when II is weak [6], and 3) the self-consistent cooling when II is strong [7, 8]. In the following, we will first formulate a generalized macroscopic model and show that many of the past II models either are its special cases or share some of its crucial characteristics. A unified view will then be built and potential unified models will be discussed.

II. A Generalized Macroscopic Model

The high-energy part of the carrier distribution can be treated differently from the entire distribution using a perturbation approach (for a more complete review, see [5] and references therein). If the mean energy is close to the definition of the *high energy*, this treatment is somewhat blurred and questionable. Nevertheless, from the classical point of view [3], as long as the bulk II coefficient is proportional to $\exp(-C/F)$ instead of $\exp(-C/F^2)$[4] where F is the electric field and C is an arbitary constant, the two-population description should be more accurate than the one-population model.

The probability P_h of carriers obtaining energy E_h from the electric field $F(x)$ without lossing energy due to scattering can be estimated by

$$E_h \;=\; -q\int_{x-L_h}^{x} F(x')dx' \;=\; -q\bar{F}L_h \;=\; q(\psi(x)-\psi(x-L_h)) \tag{1}$$

$$P_h \;=\; \exp(-\int_{x-L_h}^{x} 1/\lambda_{eff}\,dx') \;=\; \exp(-L_h/\bar{\lambda}_h) \tag{2}$$

where L_h is the distance for carriers to attain E_h, ψ is the potential and λ_{eff} is the mean free path for the carriers *not effectively* scattered which includes the effects of both lucky (no scattering) and drift (scattering that does not severely affect the energy gaining process) parts [5, 9]. $\bar{\lambda}_h$, the mean value of λ_{eff} within $(x-L_h,\,x)$, is expected to have a rather weak dependence on E_h in reasonable ranges if phonon scattering is dominant in determining λ_{eff}. It may have a dependence on x only if impurity and surface scatterings are very strong.

III. Comparison with Past II Models

If we assume that hot carriers have an *infinite rate* to impact ionize once their energy reaches E_{th}, then the II coefficient will be $\alpha_I = P_I/L_I = \exp(-L_I/\bar{\lambda}_I)/L_I$ with E_h and L_h replaced by E_{th} and L_I in (1) and (2), which becomes the classical lucky electron model and the nonlocal field (NLF) model in [10], where a 2-D generalization is implemented. This is not to be confused with the lucky electron model in [13], where a specific field profile has been assumed for MOSFET applications. It was thought that energy calculation in (1) of the lucky electron model should start from the average energy $3k_BT_c/2$ instead of 0 to better model the drift and thermionic contributions to hot carriers [4, 5]. However, this modification mixes the two-population concept and does not show correct asymptotic behavior as discussed below. Intuitively, the average energy $3k_BT_c/2$ cannot be added to the hot carrier energy directly since it is randomized with respect to the direction of the electric field.

The infinite II rate beyond E_{th} however precludes hot carriers with energy larger than E_{th} (no thermionic gate current in MOSFET). To include a *finite II rate*, separate population and energy conservation equations can be explicitly solved for carriers with energy larger than a *threshold* energy [11] and the II coefficient is parametrized as functions of the mean energy of the *tail* carrier population (TEHD). In [11], however, the tail population is estimated from a Monte Carlo (MC) calculation with some pre-selected matching parameters instead of from (1) and (2). The parametrization step from MC, although good for a particular field profile, is hard to be generalized for arbitary applications. To include a soft threshold [4, 6], the *threshold* energy of the tail electron model can be pushed below bandgap [12]. This modification is still under investigation.

In Table 1 we list the problems encountered in both nonlocal and local II models [10, 11]. The local temperature (LT) model significantly overestimates the diode breakdown voltage, while the local field (LF) model overestimates MOSFET substrate current. The parameter m in the power-law (PL) model [17] is very device specific and can be regarded as a more engineering approach with little physical base. In Fig. 1 we show the generation rate in a $0.4\mu m$ nin diode, and in Figs. 2 and 3 the results for typical conventional and LDD MOSFET substrate currents are shown. The asymptotic behavior of these models in view of the generalized macroscopic model is described below.

The field variations can be characterized by $\lambda_F = \left|F/\frac{dF}{dx}\right|$. We will first consider only monotonic profiles of F. For pn junctions, λ_F is close to the depletion region width W_d, which in Si is typically larger than 2000 Å before Zener breakdowns [19]. If $\lambda_F \gg L_I$, which is around 70-200 Åfor silicon, $\bar{F}$ in (1) can be very well estimated by the local field. However, the field variation for conventional MOSFETs (see Fig. 4 for typical F profiles) is much smaller. The apparent success of $\alpha_I(T_c)$ for MOSFETs can be seen from the approximate solution [14, 15, 16],

$$T_c(x) = T_0 + \frac{2q}{5k_B}\int_0^x F(x')\exp(\frac{x'-x}{\lambda_T})dx' \tag{3}$$

where $\lambda_T = \frac{5}{3}v\tau_w$ with v being the average carrier velocity and τ_w the energy relaxation time. If λ_T is quite large in comparison with λ_F and L_I, T_c provides a detour to evaluate $\bar{F}$ in (1). However, if $\lambda_F \gg \lambda_T$ as in pn junctions, α_I is severely underestimated. For moderate field variations such as in LDD MOSFET (Fig. 5), adjustment of parameters in LF, LT and PL is necessary and these models lose their predictivity.

From the asymptotic cases of gradual and abrupt field variations, it is clear that the LT model is valid only because it provides an estimation of $\bar{F}$ in (1), not because it represents also the random part of the mean energy. If $3k_BT_c/2$ is added directly to E_h in (1), we have double-counted the contribution from the electric fields. This is manifest in Fig. 1 for the nin case, where the field variation can be considered as gradual. When the parameter set of NLF generates good agreement with MC in nin diodes (the same parameter set has been used in LF, LT and NLF to fit the bulk case), the further addition of $3k_BT_c/2$ to E_h will make the generation rate far exceed the results of other models. Even if the E_{th} is tuned to $1.75eV$, NLF with T_c addition still predicts much larger generation rate than the MC results.

NLF will produce the invariant characteristic curve for long-channel MOSFET's [18] if the field shape is similar. LF and LT will have invariance if the maximum of F or T_c is close. Entering into deep-submicron range, variation from the invariant curve [20] cannot be explained by LF or LT. Whether NLF and TEHD can predict the deep-submicron variation still needs more careful characterization. Direct self-consistent implementation of the generalized macroscopic model in multi-dimensions is physically clear but may affect computational efficiency owing to many additional far-neighbor couplings. More investigation is necessary for different implementation strategies. Yet difference between T_c and the homogeneous carrier temperature $T_c^{(h)}$ determined only by F in bulk case, is a good indicator for the nonlocality in (1). A local empirical model $\bar{F}_{eff}(T_c, T_c^{(h)})$ preserving asymptotic correctness in two extreme cases of λ_F and limited invariance for long-channel MOSFETs, such as $(\frac{2}{(1/T_c^{(h)})^\alpha + (1/T_c)^\alpha})^{1/\alpha}$, will be able to reasonably fit a wide range of different devices and technologies. This model is still under investigation.

IV. Summary

We have explained the past II models in a unified framework and suggested potential generalized II models. For applications in deep-submicron or high-power silicon technologies, the II model with asymptotic correctness to gradual and abrupt field variations, will greatly enhance the predictivity of device simulation.

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Models	Bulk	Diode BV	Conventional MOSFET	LDD MOSFET
Local Field	Yes	Yes	Overestimate	Adjustable
Local Temperature	Map	Overestimate	Yes	Adjustable
Power Law [3]	$m = 1$	$m = 1$	$m \approx 1.2 \sim 1.5$	$m \approx 1.1 \sim 1.3$
Nonlocal Field	Map	?(self-consistency)	Yes	Yes
TEHD	Map	?(self-consistency)	Yes	Yes

Table 1: Comparison of applicability of II models.

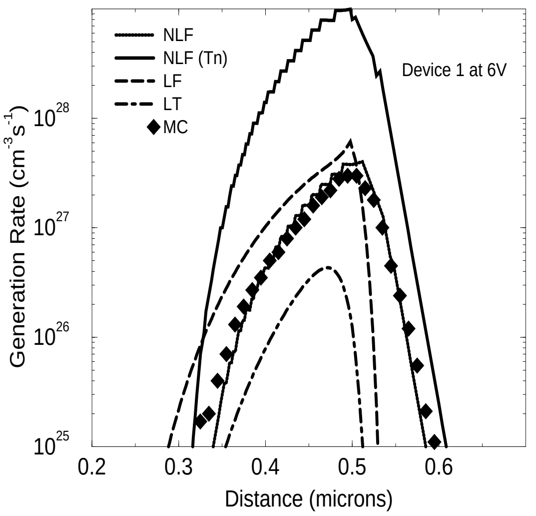

Fig. 1: II rate of an 0.4 μm nin device.

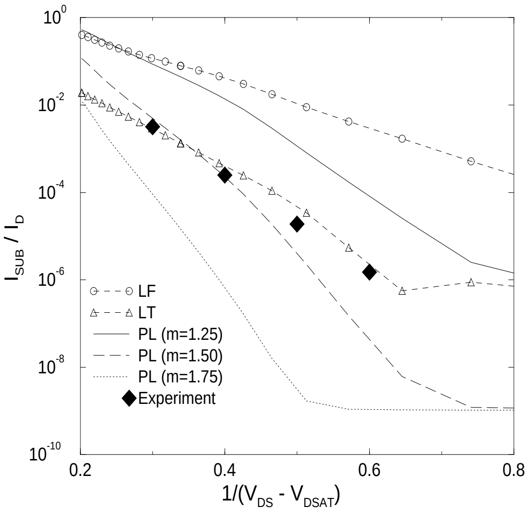

Fig. 2: Substrate current calculations of a conventional MOSFET. L_{eff}: 0.5 μm; t_{ox}: 152 Å; N_{Asub}: $2 \times 10^{17} cm^{-3}$.

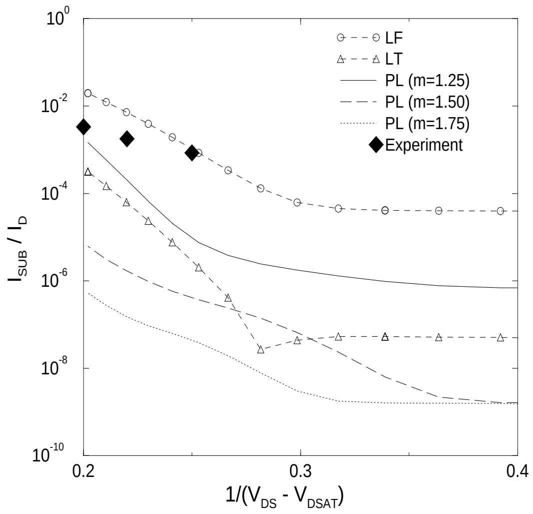

Fig. 3: Substrate current calculations of a LDD MOSFET. L_{eff}: 0.6 μm; t_{ox}: 152 Å; N_{Asub}: $2 \times 10^{17} cm^{-3}$.

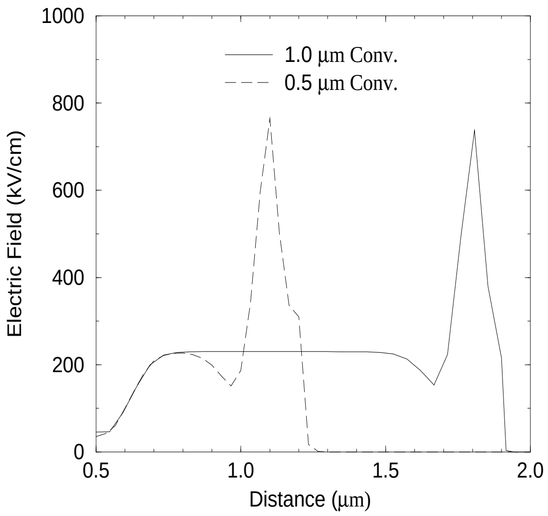

Fig. 4: Electric field profiles of the conventional MOSFETs in Fig. 2 measured at 10 Å below the oxide/silicon interface. $V_{ds} = 5V$; $V_{gs} = 1V$.