A NON-LOCAL FORMULATION OF IMPACT IONIZATION FOR SILICON

Paul Scrobohaci and Ting-wei Tang
Dept. of Electrical & Computer Engineering
University of Massachusetts, Amherst, MA 01003 USA

The continuous reduction in the size of semiconductor devices has led to an increased interest in hot–electron effects such as Impact Ionization (II). Monte–Carlo (MC) simulations provide physically correct results but require extensive computer time since II is due to high energy electrons which are statistically a minority. Most of the existing II models attempt to relate the II rate γ_{ii} or the II coefficient α_{ii} to macroscopic variables available from hydrodynamic (HDE) simulations (such as the electric field (E) in the model proposed by Chynoweth [1] or the total average electron energy (w) in the model proposed by Slotboom et.al. [2]). The predictions of such models are close when they are compared to MC data through quantities such as the multiplication factor M-1 or the substrate current which are obtained by integration of the II coefficient over the device length. However comparisons at the local level show significant discrepancies which are probably leveled out in the integration. The field distribution obtained for one of the simulated $n^+ - n^- - n^+$ devices is shown in Fig. 1. The discrepancies in the energy model are clearly shown in Fig.2 where γ_{ii} is plotted versus w^{-1} for the aforementioned device and for various biases. The II rate is not a single–valued function of w^{-1}, i.e., different γ_{ii} values are attained on the decreasing and increasing field sides for the same w values, and the hysteresis is quite large (the ordinate scale is logarithmic).

Only the electrons with energies larger than or equal to the II threshold energy (ϵ_{thr}) contribute to II. In most cases the electrons in the high energy subpopulation (HES), defined above, are a minority. Therefore the information conveyed by the *total average electron energy is irrelevant* to II. We propose the average energy of the HES, $\tilde{w}$, as the appropriate variable for modeling. The plot in Fig.3 (corresponding to a worst case) confirms our proposal. A universal device and bias independent function Γ, accounting for the non–local behavior of $\tilde{\gamma}_{ii}$ has been found allowing us to express $\tilde{\gamma}_{ii} = \tilde{\gamma}_{ii}^{\,h}(\tilde{w}) + \Gamma(\tilde{w})\frac{d\tilde{w}}{dx}$ according to the method recently proposed by Tang and Ramaswamy [3]. The superscript h stands for homogeneous, i.e., bulk silicon values.

In order to obtain $\tilde{w}$, a transport model is developed by obtaining the 0-th and 2-nd order moments of the Boltzmann transport equation (BTE) for the HES:

$$\frac{d\tilde{J}}{dx} = \tilde{n}\tilde{C}_n - \tilde{n}I_n \tag{1}$$

and

$$\frac{d(\tilde{J}\tilde{w})}{dx} - F\tilde{J} = \tilde{n}\tilde{C}_\epsilon - \tilde{n}I_\epsilon, \tag{2}$$

where I_n and I_ϵ are the electron flux and the energy flux respectively crossing the $\epsilon = \epsilon_{thr}$ boundary during free–flights. The unknowns in the system are $\tilde{n}$, $\tilde{J}(= \tilde{n}\tilde{V})$ and $\tilde{w}$. The above equations are supplemented by a closure equation relating empirically $\tilde{n}$ to $\tilde{w}$:

$$\tilde{n} = \tilde{n}^h(\tilde{w})\left[1 + \nu_1(\tilde{w})\frac{d\tilde{w}}{dx}\right] + \nu_2(\tilde{w})\frac{d^2\tilde{w}}{dx^2}, \tag{3}$$

where ν_1 and ν_2 are universal functions of $\tilde{w}$.

A specific solver has been implemented for the system formed by Eqs.(1)–(3) in one dimension and the $\tilde{w}$ values obtained were used in the calculation of non–local γ_{ii} values. The γ_{ii} values obtained from the model are very close to the MC values as can be seen in Fig.4. The band–structure (BS) used in the MC simulation is the one proposed by Brunetti et.al. [4] and the II mechanism is a version of the model proposed by Sano et.al. [5], adapted to our spherical BS.

Our purpose is to show that $\tilde{w}$ is the appropriate variable for the II model and that a system of transport equations allowing us to determine $\tilde{w}$ can be found. The introduction of a more accurate BS and II mechanism will only require recalibration of some of the transport coefficients presented here; the fundamental idea and the model will remain the same.

Finally, this model will be extended to two dimensions and applied to the prediction of breakdown phenomena in BJT's and hot-carrier effects in MOSFETS.

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References

[1] A. G. Chynoweth, *Phys. Rev.*, **109**, 1537, (1958).

[2] J. W. Slotboom, G. Streutker, M. J. v. Dort, P. H. Woerlee, A. Pruijmboom, D. J. Gravesteijn, *IEDM*, pp. 5.4.1.–5.4.4., 1991.

[3] T.-w. Tang and S. Ramaswamy, *Proceedings of NASCODE VIII*, pp. 50–51, May 1992.

[4] R. Brunetti and C. Jacoboni, *Solid-State Elect.*, Vol. 32, No. 12, pp. 1663–1667, 1989.

[5] N. Sano, T. Aoki, and A. Yoshii, *Appl. Phys. Lett.*, Vol. 55, No. 14,pp. 1418–1420, Oct 1989.

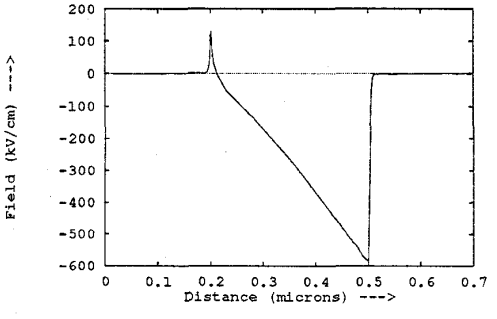

Figure 1: Field profile for self-consistent MC simulations of an abrupt $n^+ - n^- - n^+$ device at $V_{bias} = 8V$.

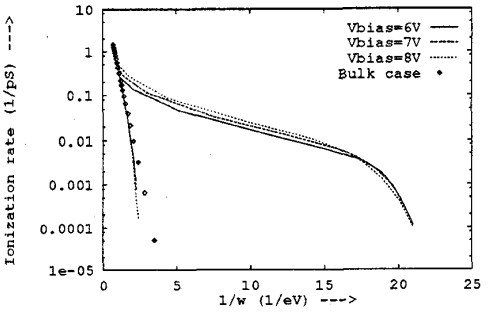

Figure 2: Impact Ionization rates obtained from self-consistent MC simulations of an abrupt $n^+ - n^- - n^+$ device vs. total average electron energy.

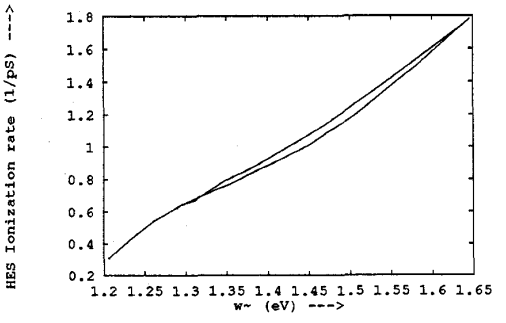

Figure 3: II rate vs. average energy of the high energy electron subpopulation (case of widest hysteresis loop).

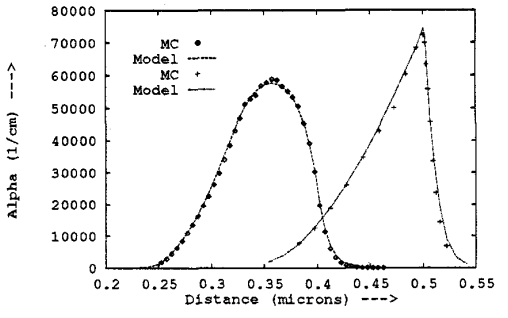

Figure 4: Comparison between II coefficients obtained from MC and our model for an abrupt profile and an LDD profile.